Aalto University
School of Engineering

Wertti Bask

# Confirming the Functionality of Variable Air Volume Ventilation Systems with Field Studies

Master's Thesis
Aalto University
School of Engineering
Department of Energy Technology

Thesis submitted as a partial fulfilment of the requirements for the degree of Master of Science in Technology

Espoo, 27.5.2019
Supervisor: Professor Risto Kosonen
Advisor: D.Sc. Simo Kilpeläinen

Aalto-yliopisto
Insinööritieteiden
korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

**Abstract of master's thesis**

**Author** Wertti Bask

**Title of thesis** Confirming the Functionality of Variable Air Volume Ventilation Systems with Field Studies

**Degree programme** Advanced Energy Solutions

**Major/minor** Sustainable Energy in Buildings and Built Environment **Code** ENG3068

**Thesis supervisor** Professor Risto Kosonen

**Thesis advisor(s)** D.Sc. Simo Kilpeläinen

**Date** 27.5.2019 **Number of pages** 88 **Language** English

People spend up to 90 % of their time indoors. Indoor environment has a significant impact in one's health, comfort and productivity. Only in Europe two million disability adjusted life years are lost every year due to poor indoor air quality. With only a 600 ppm increase in $CO_2$ concentrations can cause a significant decrease in decision-making performance. It can be concluded that ventilation systems have an enormous impact on people's health and wellbeing by contributing to the quality of indoor air.

Ventilation systems also have a distinct impact on the world's energy consumption. Approximately 40 % of all energy produced is used for buildings to manage indoor climate and it produces around 30 % of the total greenhouse house gas emissions. In Nordic countries ventilation contributes approximately of 35-50 % of building's total energy consumption hence ventilation systems have a big role in controlling the climate change. EU's energy performance of buildings directive states that in 2020 all new buildings must be near-zero energy buildings, which develops a lot of pressure for increasing energy efficiency with different methods.

Ventilation systems need to become more energy efficient without compromising indoor air quality. Demand controlled ventilation (DCV) systems can increase energy efficiency significantly compared to constant air volume ventilation systems without compromising indoor air quality. Unfortunately, DCV systems have not been working as desired and there have been problems with controllers, sensors, subsystems and components. DCV systems can be very complex which leads to notable challenges with fault diagnostics. This thesis's goal is to analyze the functionality of variable air volume systems.

The results of this study show that the DCV systems do not work as designed in most of the analyzed buildings. The most common problem was that the airflows did not match the designed airflows and the relation between supply and exhaust airflows were too high or low. On the other hand, room conditions were acceptable in most of the rooms showing that the functionality cannot be defined by measuring room conditions. This study shows that DCV systems can reduce energy efficiency without reducing indoor air quality but due to their complexity DCV systems many of them do not work properly in practice.

**Keywords** Demand controlled ventilation, indoor air quality, thermal comfort, field test, system performance

**Aalto-yliopisto**
**Insinööritieteiden korkeakoulu**

**Aalto-yliopisto, PL 11000, 00076 AALTO**
**www.aalto.fi**

**Diplomityön tiivistelmä**

**Tekijä** Wertti Bask

**Työn nimi** Tarpeenmukaisen ilmanvaihdon toimivuuden määrittäminen kenttämittauksilla

**Koulutusohjelma** Advanced Energy Solutions **Koodi** ENG3068

**Pääaine** Sustainable Energy in Buildings and Built Environment

**Työn valvoja** Professori Risto Kosonen

**Työn ohjaaja(t)** TkT Simo Kilpeläinen

**Päivämäärä** 27.5.2019 **Sivumäärä** 88 **Kieli** Englanti

Ihmiset viettävät noin 90 % ajastaan sisätiloissa. Sisäilmastolla on merkittävä vaikutus ihmisten terveyteen, mukavuuteen ja tuottavuuteen. Pelkästään Euroopassa kaksi miljoonaa toimintakykyistä elinvuotta menetetään joka vuosi heikon sisäilman laadun vuoksi. Vain 600 ppm:n nousu $CO_2$ pitoisuudessa heikentää päätöksentekokykyä merkittävästi. Voidaan siis todeta, että ilmanvaihtojärjestelmällä on merkittävä vaikutus ihmisten terveyteen ja hyvinvointiin vaikuttamalla sisäilman laatuun.

Ilmanvaihtojärjestelmillä on myös merkittävä vaikutus maailman energiankulutukseen. Arviolta 40 % kaikesta tuotetusta energiasta kuluu rakennusten sisäilmaston hallintaan, mikä tuottaa noin 30 % kasvihuonepäästöistä. Pohjoismaissa ilmanvaihtojärjestelmään kuluu noin 35-50 % rakennuksen koko energiankulutuksesta, joten ilmanvaihtojärjestelmillä on suuri vaikutus ilmastonmuutokseen. EU direktiivi EPBD:n mukaan vuonna 2020 kaikkien uusien rakennusten tulee olla lähes nollaenergiarakennuksia tarkoittaen, että ilmanvaihtojärjestelmien tulee kehittyä entistä energiatehokkaimmiksi.

Ilmanvaihtojärjestelmien tulee olla entistä energiatehokkaampia kuitenkin heikentämättä sisäilman laatua. Kysyntään perustuva (DCV) ilmanvaihtojärjestelmä voi lisätä energiatehokkuutta verrattuna perinteisempään tasailmamääräiseen ilmanvaihtojärjestelmään heikentämättä sisäilman laatua. Valitettavasti DCV järjestelmät eivät ole toimineet halutulla tavalla ja niissä on todettu ongelmia ohjaimissa, sensoreissa, alijärjestelmissä ja komponenteissa. DCV järjestelmät voivat olla hyvinkin monimutkaisia johtaen huomattaviin ongelmiin virhediagnooseissa. Tämän diplomityön tavoitteena on selvittää muuttuvien ilmamääräisten ilmanvaihtojärjestelmien toimivuus.

Tämän tutkimuksen tulokset osoittavat, että DCV järjestelmät eivät toimi suunnitellulla tavalla suurimmassa osassa tutkituista rakennuksista. Yleisin ongelma on, että mitatut ilmavirrat eivät täsmänneet suunniteltuja ilmavirtoja, sekä tulo- ja poistoilmavirtojen suhteet olivat usein liian suuret tai pienet. Toisaalta, suurimmassa osassa kohteista sisäilmaston olosuhteet olivat hyväksyttävät osoittaen, että ilmanvaihtojärjestelmän toimivuutta ei voi määrittää pelkästään tutkimalla sisäilmastona olosuhteita. Tämä tutkimus osoittaa, että DCV järjestelmät voivat vähentää energiankulutusta heikentämättä sisäilman laatua, mutta järjestelmien monimutkaisuuden takia useat järjestelmät eivät toimi käytännössä.

**Avainsanat** Muuttuva ilmamäärä, sisäilman laatu, lämpötilamukavuus, kenttätutkimus, paineella ohjattu DCV-järjestelmä

# Foreword

This master's thesis has been carried out for Sisäilmayhdistys ry between October 2018 and March 2019. I want to thank Sisäilmayhdistys ry for giving me this opportunity. The thesis was done in co-operation with Aalto University.

I want to thank both, the advisor Simo Kilpeläinen, and the supervisor Risto Kosonen for their help. Especially Simo has provided me with all the practical help necessary for which I am truly grateful. Their help, professional views and guidance have been invaluable.

I want to thank Marianna Tuomainen from City of Helsinki and ACRE for providing all the necessary material and contacts for this study. Marianna has been very active and obliging, which has been essential for the progression of this thesis.

I want to thank my mom and brother for their help, support and advices. I want to thank my dad for providing me support and insight.

Finally, I want to thank my girlfriend, Annemari, for supporting me through this journey. Without my family I would not be here writing these words.

I am very grateful for all the friends that I have made during my time studying in Aalto University and also from all the experiences that I have had during my time being a student. It has been a wonderful experience, which I will cherish.

Helsinki 27.5.2019

*Wertti Bask*

Wertti Bask

# Table of Contents

# Symbols

| | | |
|---|---|---|
| $t_{op}$ | [°C] | Operative temperature |
| $t_u$ | [ºC] | Outdoor temperature |

# Abbreviations

| | |
|---|---|
| ACRE | Aalto University Campus and Real Estate |
| AHU | Air handling unit |
| VAV | Variable air volume |
| CAV | Constant air volume |
| SBS | Sick building syndrome |
| OIH | Open Innovation House |
| IAQ | Indoor air quality |
| EU | European Union |
| VOC | Volatile organic compound |
| WHO | World Health Organization |
| SFS | Finnish Standards Association |
| FINVAC | Finnish Association of HVAC Societies |
| DCV | Demand controlled ventilation |
| MOV | Manually operative ventilation |
| SPR | Static pressure reset |
| SFP | Specific fan power |
| CRE | Contaminant removal effectiveness |
| ACE | Air change efficiency |
| GHG | Greenhouse gas |
| nZEB | Nearly zero energy building |
| EPBD | Energy performance of buildings directive |

## List of Figures

# List of Tables

# 1 Introduction

Approximately 40 % of all energy produced is used for buildings to manage indoor climate (Wyon, 2004) and it produces around 30 % (Mattinen, Heljo and Savolahti, 2016) of the total greenhouse house gas (GHG) emissions (Ahmad *et al.,* 2016). In Finland the long-term goal is to reduce GHG emissions overall by at least 80 % by 2050 compared to 1990 (Finlex, 2015). Most of the buildings in Europe are over 50 years old and 75 % of all buildings are considered energy inefficient. By renovating old and energy inefficient buildings GHG emissions can be lowered substantially (European Commission, 2017). On the other hand, European Union (EU) directive 2018/844 states that the buildings stock in EU will be carbon free by 2050 (European Union, 2018). A key objective for EU to achieve this goal is by increasing the renovation rate of buildings to 2-3 % per year until 2030 (Artola *et al.,* 2016). In EU the energy performance of buildings directive (EPBD) is the main legislation covering the improvement of energy efficiency in buildings stating that all new buildings must be near-zero energy buildings (nZEB) after 2020 (Directive, 2002).

In the Nordic countries existing office buildings' ventilation contributes for approximately 35-50 % of the buildings' total energy consumption (Schild and Mysen, 2011). When increasing energy efficiency for buildings, the role of indoor environment must not be undermined (Energiatehokkuus, 2012). People spend up to 90 % of their time indoors (Sundell, 2004). Indoor climate has a big impact on one's health, productivity, comfort and learning consequently the high quality of indoor environment is essential (Arif *et al.,* 2016).

Problems with indoor air quality (IAQ) can originate from many different sources like structural damage with the building, poor cleaning, material emissions and ventilation. In public and especially school buildings occupants cannot be exposed to harmful indoor environment hence the possible problems need to be attended quickly (Hilden, 2014). Dampness, mold, dry or stuffy inside air, dust, fiber, smoke and industrial fiber are all factors that affect IAQ (Reijula *et al.,* 2012).

To maintain a proper IAQ and at the same time to increase energy efficiency, variable air volume (VAV) ventilation systems have become popular solution (Okochi and Yao, 2016). Most VAV ventilation systems are demand controlled ventilation (DCV) systems where the airflow rates are continuously matched with actual demand (Maripuu, 2011). DCV allows reducing ventilation for empty spaces or spaces where less ventilation is required saving energy (Maripuu, 2009).

A DCV system is much more complicated than a traditional ventilation system and hence it has a higher risk of malfunctioning. A malfunction can occur on different layers of the system like controllers, sensors, subsystems and components. Most of the time faults are caused by poor system design, maintenance, application or operation. Faults can be classified as abrupt faults that happen quickly or faults that develop over time. (Okochi and Yao, 2016). Faults can lead to energy inefficiency and poor indoor environment, which defeats the purpose of investing into a DCV system. Detecting faults can lead to energy savings of up to 10-40 % (Liang, Meng and Chang, 2017).

The energy consumption of buildings will be reduced significantly in the future and ventilation constitutes a big role in it. It is challenging to increase energy efficiency while trying to maintain a proper indoor environment which requires more complex ventilation systems. The errors with DCV systems may lead to energy inefficiency and poor indoor environment. Hence, it is important to recognize the advantages, disadvantages and challenges of DCV systems.

## 1.1 Research questions and objectives

The main research objective of this thesis is to study the performance of VAV-ventilation systems in occupied buildings. The buildings that are studied are public buildings. The objective is to analyze the functionality of the ventilation system in buildings where no faults are known. The ventilation systems from eight different buildings will be analyzed and the functionality defined. This thesis will not give recommendations on solving the faults nor study how they are originated. The main research question is:

*Do variable air volume ventilation systems operate as designed and in desirable manner?*

Another objective of this thesis is to improve the measurement strategy for it to become more reliable and efficient.

## 1.2 Structure of thesis

This thesis consists of a literature review and theory part and an empirical research part. The literature review and theory is covered in chapters 2 and 3. Methodology is introduced in chapter 4. Measurements and their results are covered in chapters 5, 6 and 7.

Chapter 2 covers indoor environment and its effects on health and productivity. The chapter also includes different building codes, standards, guides and regulations considering indoor environment and ventilation.

Chapter 3 covers the basics of VAV ventilation systems. It presents DCV systems with different operability and what factors affect its effectiveness, energy efficiency and functionality.

Chapter 4 presents the methodology of the carried out measurements. It presents how the measurements were done and why the utilized methods were applied.

Chapter 5 presents the measurement results. Every building chosen to study has its own chapter for analysis.

In chapter 6 the measurement results are discussed and chapter 7 collects the measurement results together for an overall conclusion.

# 2 Indoor air quality

Nowadays humans spend more than 80 % (Wang, Ang and Tade, 2007) or in some regions, even over 90 % (Sundell, 2004) of their time indoors (home, office, school, car, etc.). Most of the exposure takes place in homes (Mølhave and Krzyzanowski, 2003). In some cases the IAQ is actually worse than the respective air quality outside but this is very circumstantial. Anyhow, it is crucial to have properly working ventilation systems to improve indoor air environment to result in better well-being of the residents without compromising their health. (Wang, Ang and Tade, 2007). Even the World Health Organization states (WHO) principles considering indoor air (WHO, 2000).

**Principle 1: Under the principle of the human right to health,** everyone has the right to breathe healthy indoor air (WHO, 2000).

**Principle 2: Under the principle of respect for autonomy ("self-determination"),** everyone has the right to adequate information about potentially harmful exposures, and to be provided with effective means for controlling at least part of their indoor exposures (WHO, 2000).

## 2.1 Effects on health

Indoor environment probably has the biggest effect on one's health. People have known for a long time for example that smoke or carbon monoxide is not healthy for you but studies are now able to show more subtle and long-term health effects of different pollutants. Some pollutants are not as safe as once have been thought. (Spengler, Samet and McCarthy, 2001)

Only in EU two million disability adjusted life years are lost every year due to poor IAQ. This includes mortality and morbidity due to $CO_2$ exposures, volatile organic compounds (VOC), dampness and mold, smoke, radon, pollen, allergies, asthma, lung cancer and acute intoxication and respiratory diseases due to particulate matter. (Hänninen and Asikainen, 2013)

Children attending schools near high traffic density areas have a higher chance to develop childhood asthma and wheeze due to pollutants (Gasana *et al.,* 2012). These pollutants can be prevented from invading indoor air with a proper ventilation system and filtration. Also, fungal particles that can be formed inside a building have a positive effect on developing respiratory symptoms including respiratory infections. (Chatzidiakou, Mumovic and Dockrell, 2014)

These health risks can be reduced significantly by adjusting ventilation, changing proper filters for air intake, and with focusing on the indoor sources of exposures. All of these approaches can have significant increases on IAQ but the benefit of decreasing health risks increases from 20 % to 50 % when all of them are implemented at the same time. (Hänninen and Asikainen, 2013)

On the other hand, some people suffer from sick building syndrome (SBS). With SBS occupants can suffer symptoms of illness without any explicit reason. The IAQ can be perfect including all the other parameters affecting occupant comfort and health. In extreme cases the occupant can receive these symptoms just by being near the building. (Finnegan, Pickering and Burge, 1984). The symptoms can be skin irritation, sore throat or eye, runny nose, headaches, loss of concentration and lethargy. The symptoms usually disappear quickly after the occupant exits the building (Kosonen, 2018).

## 2.2 Effects on productivity

Indoor environment is also expected to be comfortable. This includes proper temperature, humidity, lighting and sound but the focus will be on IAQ and its effect on productivity. Multiple studies state that bad IAQ may lead to poor productivity at school or work with various different ways. There are considerable benefits from a good IAQ (Wyon, 2004).

Simply by controlling $CO_2$ concentrations can improve occupants' cognitive performance. Already at 1000 ppm compared to 600 ppm average decision-making performance is significantly decreased. At 2500 ppm compared to 600 ppm some decision-making performance can be categorized as dysfunctional. (Satish *et al.,* 2012). Table 1 shows approximate $CO_2$ concentrations in different rooms that are above outdoor air $CO_2$ concentration. Outdoor $CO_2$ concentration is on average 400 ppm but this can vary a lot depending on location and time. (Persily and de Jonge, 2017). It is noticeable that 5/6 spaces in Table 1 have a $CO_2$ concentration really close or above 1000 ppm above outside $CO_2$ concentration meaning that in these rooms decision-making performance is significantly reduced.

**Table 1. $CO_2$ generation rates in different spaces (Persily and de Jonge, 2017).**

| Space type | Average CO2 generation rate [l/s/person] | Ventilation rate [l/s/person] | Steady state CO2 concentration above outdoors [ppm] |
|---|---|---|---|
| Office | 0.0048 | 7.5 | 568 |
| Conference room | 0.0048 | 3.1 | 1557 |
| Lecture classroom | 0.0042 | 4.3 | 970 |
| Lecture hall, fixed seats | 0.0041 | 4 | 1036 |
| Lobby | 0.0055 | 2.7 | 2042 |
| Auditorium seating area | 0.0048 | 2.7 | 1787 |

Also, temperature has an effect on cognitive performance. Even though individuals might prefer different temperatures, keeping air dry and cool can improve performance and reduce SBS in children. Children prefer a bit lower temperatures than adults but the temperatures should not be above 20-22 ºC in winter or 22-24 ºC in summer in order to not reduce cognitive performance. (Chatzidiakou, Mumovic and Dockrell, 2014)

## 2.3 Rules and regulations

Rules and regulations give us boundaries that need to be met in a successful ventilation system. All given information apply for non-residential buildings.

The Ministry of the Environment has rules for ventilation in “Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta” that are enforced by law which need to be applied when designing new buildings or expanding old ones. These rules do not apply for residential buildings that are occupied less than four months per year nor agricultural manufacturing facilities. (*Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta*2017)

Finnish Standards Association (SFS) publishes standards considering ventilation. Most of SFS standards are converted from global or EU’s standards. The standards are not rules that need to be utilized by law but more like guidelines. Standard SFS-EN 15251 presents standards for building’s energy efficiency and indoor environment. The standard gives different room parameters in four different categories that are shown in Table 2.

**Table 2. Description of the applicability of the categories used in SFS-EN 15251.**

| Category | Explanation |
|---|---|
| I | High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons |
| II | Normal level of expectation and should be used for new buildings and renovations |
| III | An acceptable, moderate level of expectation and may be used for existing buildings |
| IV | Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year |

The old National Building Code of Finland D2 became inoperative in year 2018 without a similar building code for replacement (D2 Suomen rakentamismääräyskokoelma, 2003). The building code became inoperative due to a reform in the constitution where all the guidelines were removed. Due to this The Ministry of the Environment started a project where The Finnish Association of HVAC Societies (FINVAC) published a guidebook to replace the guidelines that were removed with Building Code of Finland D2 (SULVI, 2017). The guidebook is called “Opas ilmanvaihdon mitoitukseen muissa kuin asuinrakennuksissa” (Seppänen *et al.,* 2017).

Finnish Indoor Climate Association, Sisäilmayhdistys ry, has also an optional classification system for ventilation that can be used as a tool when designing ventilation systems (Sisäilmayhdistys ry, 2018). The classification has three different classes that can be seen in Table 3.

Table 3. Ventilation classification and their explanations (Sisäilmayhdistys ry, 2018).

| Class | Explanation |
|---|---|
| S1 Individual indoor environment | The IAQ is excellent and no smells can be detected. There are no contamination sources or structural damages to reduce IAQ. The thermal conditions are comfortable without any occurring overheating and there is no draft. The room user can control the thermal conditions. The acoustics are excellent for the purpose of the room and the lightings can be controlled individually. |
| S2 Good indoor environment | The IAQ is good and there are no disturbing smells. There are no contamination sources or structural damages to reduce IAQ. The thermal conditions are good. There is no draft but overheating may occur at midday. The acoustics and lightings are designed for the room purpose. |
| S3 Satisfactory indoor environment | The IAQ, thermal conditions, lighting conditions and thermal conditions fulfill the necessary minimal regulations. |

### 2.3.1 Temperature

The number of dissatisfied occupants for room temperature is defined with predicted percentage dissatisfied (PPD). Predicted mean vote (PMV) predicts the mean value of votes on thermal scale. The relationship is shown in Figure 1. The figure shows that in optimal temperature 95 % of occupants are satisfies in room temperature but already when the room temperature changes ±1 ºC from optimal temperature, only 75 % are satisfied. If the change is ±2 ºC only 25 % are satisfied with the room temperature. (SFS-EN ISO 7730, 2005)

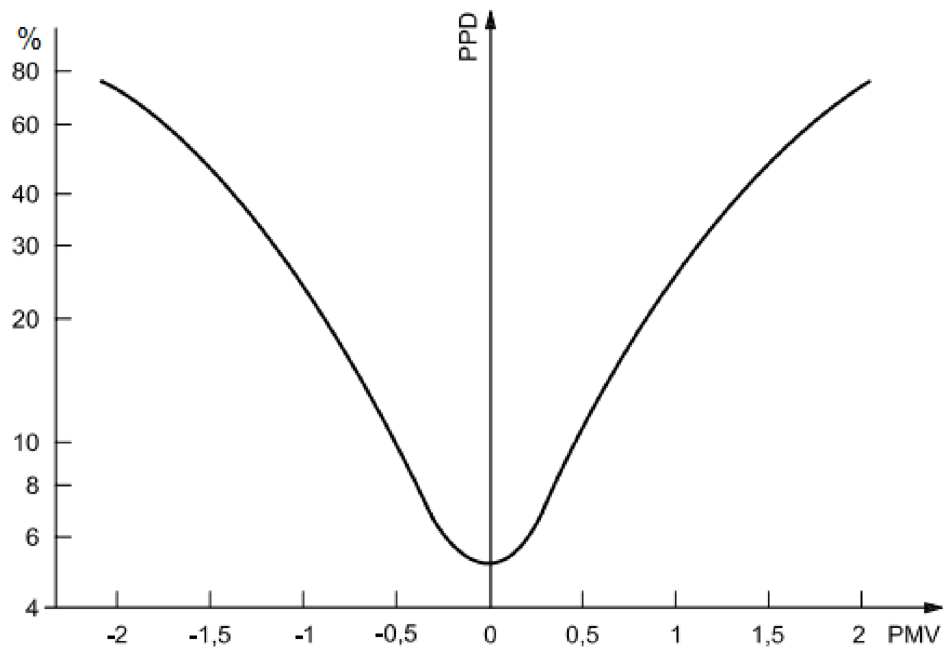

Figure 1. Percentages of dissatisfied occupants compared to PMV (SFS-EN ISO 7730, 2005).

It is impossible to specify a thermal environment that would satisfy everyone due to personal preferences. However, thermal satisfaction can be estimated with PPD and PMV and therefore it is possible to specify environments that are predicted to be satisfactory for occupants. (SFS-EN ISO 7730, 2005)

The Ministry of the Environment states that the room temperature needs to be comfortable when occupied and the movement of air, changes in temperature, temperature differences and surface temperatures must not compromise it. The basic design value for room temperature is 21 ºC on heating season. The designed controlled room temperature can be 20-25 ºC on heating season and 20-27 ºC at other times. The designed temperature ranges can be outside the given values if the room requires different temperatures for its purpose. (*Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta*2017)

Sisäilmastoyhdistys ry has defined different operative temperatures and their target values for different classes, which are shown in Table 4. Operative temperature takes into the indoor air and the temperature of surfaces (walls, floor windows, ceiling). $t_{op}$ stands for operative temperature and $t_u$ stands for outside temperature.

**Table 4. Operative temperatures and their target values within different classes (Sisäilmayhdistys ry, 2018).**

| | **S1** | **S2** | **S3** |
|---|---|---|---|
| Operative temperature $t_{op}$ [ºC] | | | 21 |
| $t_u \leq 0$ ºC | 21.5 | 21.5 | |
| $0 < t_u \leq 20$ ºC | $21.5+0.15t_u$ | $21.5+0.2t_u$ | |
| $t_u > 20$ ºC | 24.5 | 25.5 | |
| Allowed upward deviance [ºC] | | | |
| $t_u \leq 0$ ºC | <22.5 | <23 | |
| $0 < t_u \leq 15$ ºC | $22.5+0.166t_u$ | $23+0.2t_u$ | |
| $t_u > 15$ ºC | <25 | <26 | |
| Allowed downward deviance [ºC] | | | |
| $t_u \leq 0$ ºC | >20.5 | >20.5 | |
| $0 < t_u \leq 20$ ºC | $20.5+0.075t_u$ | $20.5+0.025t_u$ | |
| $t_u > 20$ ºC | >22 | >21 | |
| Maximal value of operative temperature [ºC] | | | |
| $t_u \leq 0$ ºC | <23 | <23 | |
| $0 < t_u \leq 20$ ºC | $23+0.2t_u$ | $23+0.2t_u$ | |
| $t_u > 15$ ºC | <27 | <27 | |
| $t_u \leq 10$ ºC | | | <25 (26) |
| $t_u > 10$ ºC | | | <27 (32) |
| Minimal value of operative temperature [ºC] | 20 | 20 | 20 (18) |
| Permanence of the conditions [% of operating time] | 90 % | 90 % | |

## 2.3.2 Airflows

The Ministry of the Environment states that the ventilation needs to provide a healthy, safe, and comfortable environment. Ventilation needs to remove unhealthy particulates, excess moisture, bad smells, and impurities that are generated by building materials, humans, and activity taking place in the building. For new buildings, when occupied, the rooms needs to have an airflow a minimum of 6 l/s/person or 0.35 l/s/m$^2$ if there is not a specific need for higher airflows. When unoccupied, for example during the night, the room airflows need to be a minimum of 0.15 l/s/m$^2$ but still a good IAQ needs to be maintained when the room becomes occupied. (*Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta*2017)

Standard SFS-EN 15251 presents values for preferred airflows. Table 5 shows these exemplary airflows based on their categories in Table 2. The airflows can be chosen for designed values based on category, airflow type base, (persons or square meters) and pollution rate.

**Table 5. Preferred airflows for other than residential buildings in SFS-EN 15251.**

| | | Airflows based on pollutions [l/s/m2] | | |
|---|---|---|---|---|
| Category | Airflow [l/s/person] | Very low polluting | Low polluting | Not-low polluting |
| I | 10 | 0.5 | 1 | 2 |
| II | 7 | 0.35 | 0.7 | 1.4 |
| III | 4 | 0.2 | 0.4 | 0.8 |

The FINVAC guidebook states that in office buildings the airflows need to be a minimum of 1 l/s/$m^2$ but usually airflows are defined by the number of occupants. Also, airflows are usually designed a bit higher than the minimum airflows because this can improve work efficiency for occupants. The airflows for office buildings are shown in Table 6. (Seppänen *et al.,* 2017)

**Table 6. Airflows for office buildings (Seppänen *et al.*, 2017).**

| Room space | Supply airflow rate [l/s/person] | Specific supply airflow rate [l/s/m2] | Specific exhaust airflow rate [l/s/m2] |
|---|---|---|---|
| Office | 6 | 1 | |
| Open office or something similar | 6 | 1.5 | |
| Meeting room or something similar | 6 | 3 | |
| Hallway only for transit | | 0.5 | |
| Cafeteria, break room | | 2 | |
| Storage room | | | 0.35 |
| Printing or copy room or something similar | | | 2 |

For school buildings the recommended airflow rate is 6 l/s/person but it needs to be higher for gymnasiums, art classrooms and practical classrooms (Seppänen *et al.,* 2017). The airflows are shown in Table 7.

**Table 7. Airflows for office buildings (Seppänen *et al.*, 2017).**

| Room space | Supply airflow [l/s/person] | Supply airflow [l/s/m2] | Exhaust airflow [l/s/m2] |
|---|---|---|---|
| School building | 6 | | |
| Teaching spaces | 6 | 3 | |
| Teacher's rooms | | 2 | |
| Hallways and lobbies | | 3 | |
| Hallways and lobbies only for transit | | 1 | |
| Storage spaces for outdoor clothes | | | 3 |
| Gymnasium for sports | | 2 | |
| Gymnasiums for events | 6 | | |
| Gymnasium / audience | 6 | | |
| Gymnasium sports events | 15-30 | 2-4 | |
| Lecture hall | 6 | | |
| Library, office spaces | | 2 | |
| Dining areas | 6 | 3 | |

Sisäilmastoyhdistys ry has their own propositional airflows classified for different spaces which are shown in Table 8.

**Table 8. Airflows for normal operation for spaces which fulfil nZEB criterias. For the sake of thermal control the airflows might need to be higher. (Sisäilmayhdistys ry, 2018).**

| | S1 | | S2 | | S3 | |
|---|---|---|---|---|---|---|
| **Space** | **l/s/person** | **l/s/m2** | **l/s/person** | **l/s/m2** | **l/s/person** | **l/s/m2** |
| Business premises, normal space efficiency | 16 | 1.5 | 11 | 1 | 6 | 1 |
| Business premises, great space efficiency | 14 | 2 | 9 | 1.5 | 6 | 1.5 |
| Meeting room | 12 | 4 | 8 | 3.5 | 6 | 3 |
| Break room, cafeteria | 11 | 5 | 8 | 4 | 6 | 2 |
| Hotel room | 10 | | 8 | | 6 | |
| Teaching room | 11 | 5.5 | 8 | 4 | 6 | 3 |
| Class room | 10 | | 8 | | 6 | |
| Kindergarden group spaces | 12 | 4 | 8 | 3 | 6 | 3 |
| Hallway and stairway | | 1 | | 0.5 | | 0.5 |
| Hallway and lobby | | 1.5 | | 1 | | 1 |
| Dining room and cafeteria | 11 | 5.5 | 8 | 4 | 6 | 3 |
| Heating and distribution kitchen | | 10 | | 10 | | 5-10 |
| Preparation kitchen | | 15-40 | | 15-40 | | 15-25 |
| dishwashing room | | 12-20 | | 10-15 | | 10 |
| Business premises, shop | 10 | 1-3 | 8 | 1-3 | 6 | 1-3 |
| exhibition space | | 3 | | 3 | | 2 |
| Library | | 3 | | 2 | | 2 |
| Hall (consert, theatre, movie, school) | 10 | | 8 | | 6 | |
| Foyer | | 5 | | 5 | | 5 |
| Gym | | 6 | | 6 | | 6 |
| Gymnasium, athletes | | 2.5 | | 2 | | 2 |
| Gymnasium, audience | 10 | | 8 | | 6 | |
| Patient room | 15 | 3.5 | 12 | 3 | 10 | 2.5 |
| Storage room | | 0.5 | | 0.5 | | 0.35 |

## 2.3.3 Indoor air quality

The Ministry of the Environment states that indoor air must not have particulate impurities, physical, chemical or microbiological features in quantities that would be a threat to health nor any constant unpleasant smells. Also, $CO_2$ concentration cannot exceed 800 ppm above the outdoor concentration.

Standard SFS-EN 15251 gives recommendations for $CO_2$ concentrations when humans are the main source of contaminants. These values can be used to help with energy calculations and to be used as room set $CO_2$ concentration limits. The values are shown in Table 9 where the categories are based on Table 2.

**Table 9. Exemplary $CO_2$ concentrations above outside concentrations (SFS-EN 15251, 2007).**

| Category | CO2 concentration above outside concentration [ppm] |
|---|---|
| I | 350 |
| II | 500 |
| III | 800 |
| IV | < 800 |

The standard also includes recommendations for air humidity. The designed air humidity depends on if the air needs to be humidified or dried. The values are shown in Table 10 from where the categories I-IV are defined in Table 2. Buildings like museums and churches might need to use different values. The Ministry of the Environment states that the humidity must stay within the values that are designed for the purpose of the room without causing water damage, microbe growth or a threat to health.

**Table 10. Exemplary values for relative humidity (SFS-EN 15251, 2007).**

| | Relative humidity [%] | |
|---|---|---|
| Category | When air needs to be dried | When air needs to be humidified |
| I | 50 | 30 |
| II | 60 | 25 |
| II | 70 | 20 |
| IV | > 70 | < 20 |

The FINVAC guidebook reminds that the $CO_2$ concentration cannot exceed 800 ppm above the outdoor concentration. When the ventilation is based on $CO_2$ concentration the values in Table 11 can be used to approximate $CO_2$ production (Seppänen *et al.,* 2017).

**Table 11. $CO_2$ production based on activity and metabolic power production** (Seppänen *et al.,* 2017)**.**

| Room space/action | Metabolic power [met] | Metabolic power [W] | CO2 production [l/h] |
|---|---|---|---|
| Sleeping | 0.8 | 85 | 12.4 |
| Sitting | 1 | 105 | 15.4 |
| Office work, standing | 1.2 | 135 | 18.5 |
| Teaching work | 1.4 | | 21.6 |
| Light moving | 1.6 | 165 | 24.7 |
| Walk (3.2 km/h) | 2 | 210 | 21.6 |
| Walk (5 km/h) | 3 | 315 | 46.2 |
| Walk (6.5 km/h) | 4 | 410 | 61.6 |
| Walk (8 km/h) | 6 | 630 | 92.4 |
| Sports | 7 | 735 | 107.8 |

Table 12 shows the criteria for IAQ for Sisäilmayhdistys ry's classes.

**Table 12. IAQ target values (Sisäilmayhdistys ry, 2018).**

| | S1 | S2 | S3 |
|---|---|---|---|
| $CO_2$ concentration above outdoor concentration [ppm] | <350 | <550 | <800 |
| Radon concentration | <100 | <100 | <200 |
| $PM_{25}$ [µg/m$^3$] | <10 | <10 | <25 |
| $PM_{25}$ indoors/outdoors | <0.5 | <0.7 | - |
| Permanence of the conditions [% of operating time] | 90 % | 90 % | - |

### 2.3.4 Energy efficiency

EU directive 2018/844 states that the building stock in EU must be carbon neutral by the year 2050 (European Union, 2018) and EU directive EPBD states that all buildings in governmental use need to be nZEB from 31.12.2018 forward and all new buildings must be nZEBs from 31.12.2020 forward (Directive, 2002). Ventilation has a significant role to accomplish these goals.

The Ministry of the Environment states that the supply and exhaust ventilation system's specific fan power (SFP) can be a maximum of 2 kW/(m$^3$/s). An exhaust ventilation system's SFP can be a maximum of 1 kW/(m$^3$/s). These values can be higher if it is required to maintain sufficient IAQ. A heat recovery system needs to be installed so that it recycles 45 % of the heat energy required for ventilation. This can also be achieved by installing better insulations to the building, reducing the amount of leaking air from the building or reducing the amount of heating required for ventilation. Heat recovery is not necessary for specific rooms where it is not practical. That is when the room's exhaust air is too dirty for the heat recovery system or installing the heat recovery system is not cost efficient. (Energiatehokkuus, 2012)

# 3 VAV ventilation system

Ventilation operates with a constant air volume (CAV) or a VAV principle. CAV ventilation systems have a constant airflow but the temperature of the airflow changes to meet the thermal load. VAV ventilation systems have variable air volume to control thermal load but the temperature of airflow mainly stays the same. VAV ventilation systems are now becoming more popular due to their better ability to save energy. Energy savings can be considerable since VAV ventilation systems can control airflows unlike CAV ventilation systems.

VAV ventilation systems started to gain popularity in 1980s after the energy crisis in Europe. Energy prices have only been increasing since which leads to energy efficiency to save costs. (Okochi and Yao, 2016)

Most of the VAV ventilation systems are based on a DCV system. The opposite of DCV is a manually operative ventilation (MOV) where no automation is used to control ventilation but it is controlled manually instead. The demand can be based on thermal climate, air composition or something that can be measured or predicted. (Fahlén, 2010). VAV, DCV and MOV systems are classified in Figure 2. All ventilation systems analyzed in this study are DCV systems.

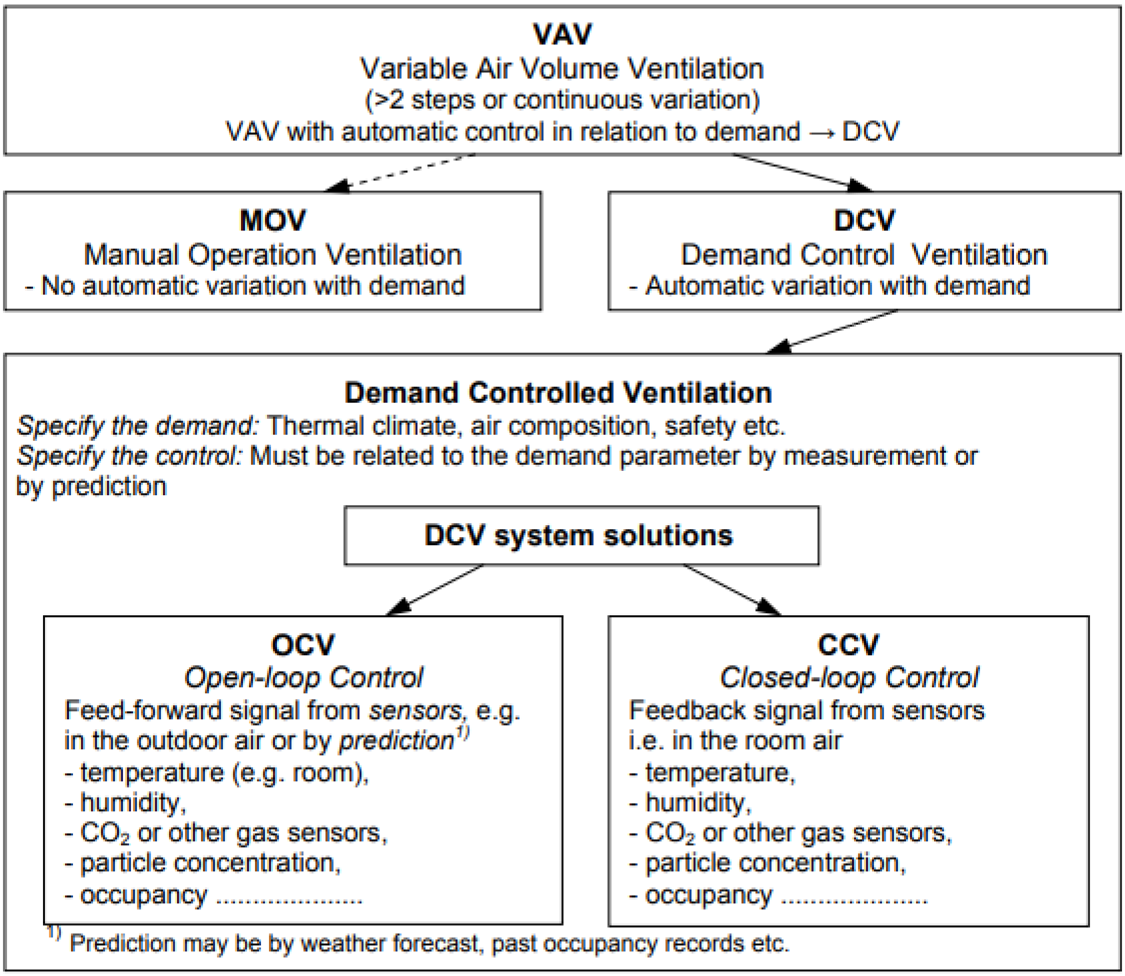


**Figure 2. Different ventilation systems (Maripuu, 2009).**

With DCV systems energy is saved by not ventilating rooms that are not occupied and by focusing the ventilation on rooms that are occupied. For example, in schools the average occupancy is only up to 30 %. (Maripuu, 2011)

## 3.1 Demand controlled ventilation

The basic idea of a DCV system is that the ventilation is based on demand, usually measured by a sensor, instead of over ventilating rooms redundantly (Fisk and De Almeida, 1998). The airflows can be controlled with occupancy, temperature, $CO_2$ concentration, humidity or by some other parameter (Maripuu, 2009).

An important part of the ventilation system is the AHU's function to clean the supply air and process the air to required temperature and humidity levels (Vuoti, 2018). After that AHU distributes the air throughout the building.

The main principle of a ventilation system and is visualized in Figure 3. A ventilation system consists of various different units such as AHU, controllers, supply fan, return fan, air ducts, air dampers, and sensors. The supply air is taken from outside with a supply fan and circulated through the AHU in to the room. Air intake can be controlled with supply fan. There are many different ways to design AHUs, but in a simple AHU the air is filtered and the air passes through a water coil. The coil exchanges heat to cool or warm the supply air to required temperature. Finally, the air is circulated to the VAV terminals and into the rooms. For air to leave the room, the return fan divides the return air to recycle air and exhaust air. Recycle air is used to reduce heat losses by recycling warm exhaust air. The ventilation system can also have a heat recovery system where supply and exhaust air do not mix. (Du and Jin, 2007)

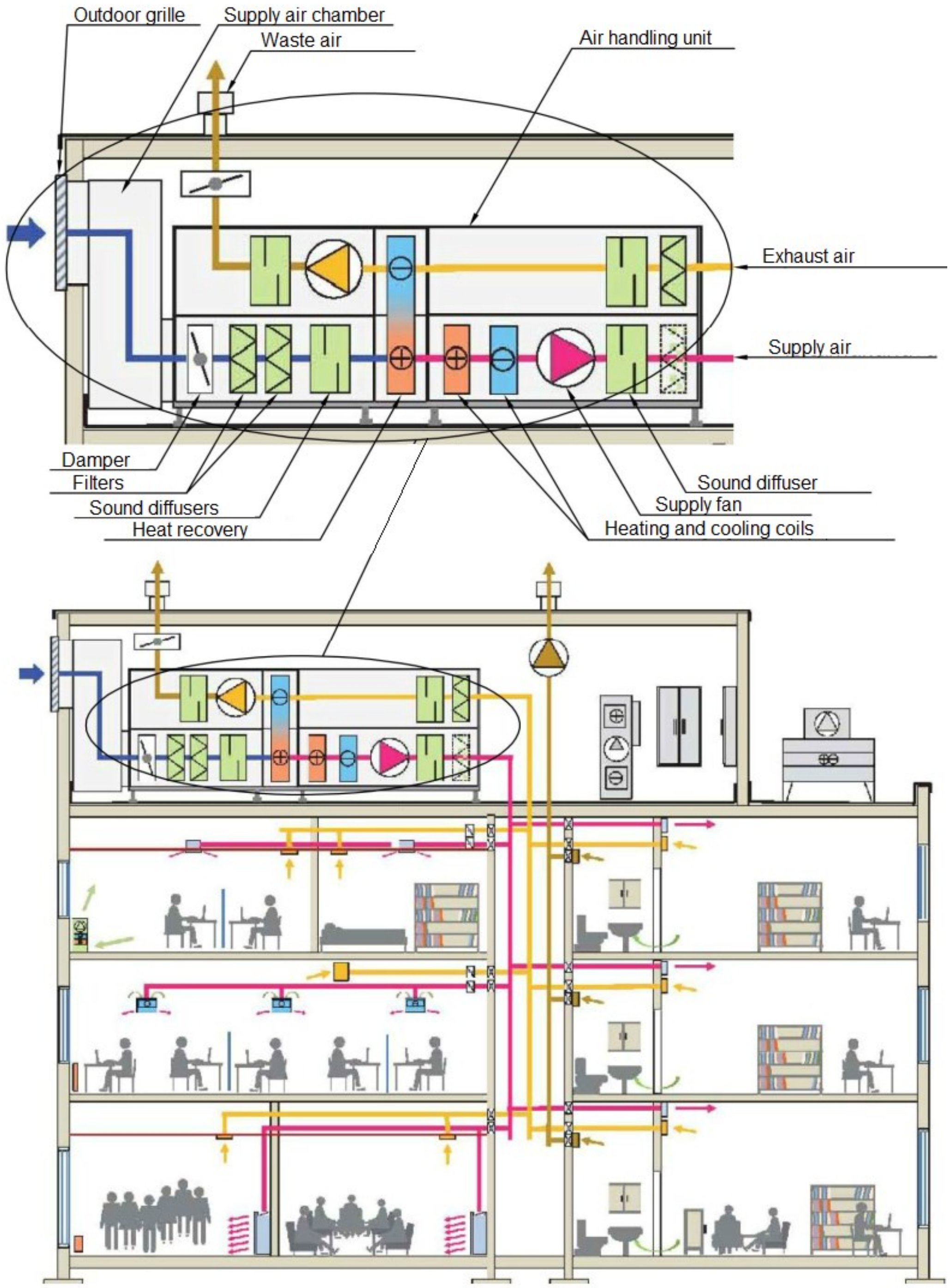


**Figure 3. Ventilation system and an example of an AHU (Vuoti, 2018).**

One way to define the efficiency of a DCV system is the correlation with SFP and fraction of maximum airflow rate. Figure 4 shows the correlation of poorly, normally, well, and ideally functioning DCV system. As it can be seen from the figure, within a good DCV system when the flow rate is reduced, the maximum SFP reduces also to save energy. With smaller airflows there are higher differences with the system's SFP compared to higher airflows. In Figure 4, the biggest changes on performance in different curves happen on low SFP levels. Fortunately, DCV systems usually use only 30-80 % from maximum SFP which means that the differences between efficiencies on low SFPs are irrelevant (Schild and Mysen, 2011).

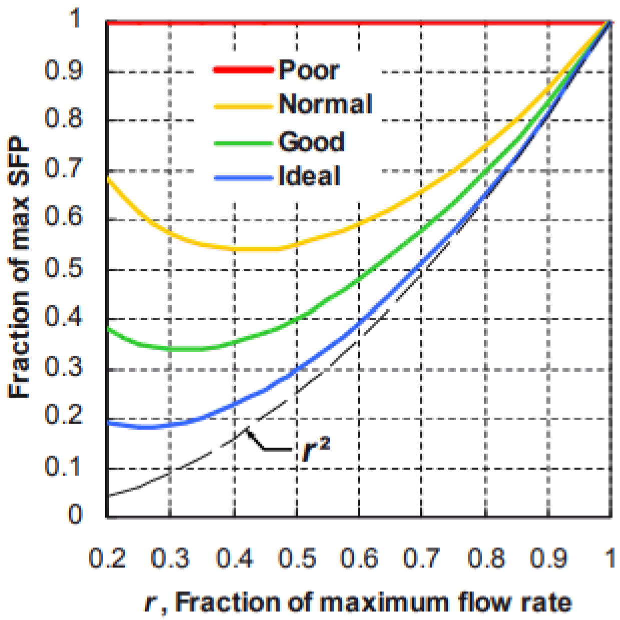


**Figure 4. Correlation with SFP and maximum flow rate with differently classified DCV systems (Schild and Mysen, 2011).**

The supply and exhaust airflows need to be in balance to not cause unwanted pressure differences over the envelope. Excess pressure can cause water to condense on cold surfaces, especially on windows, which can lead to problems with mould and microbes. Under pressure causes the air to flow from outside through the structures into the room which can bring impurities with it. Most of the ventilation systems in older buildings have been designed with slightly higher supply airflow than exhaust airflow to create a under pressure. This is because the downsides of excess pressure are seen more problematic than the downsides caused by under pressure. To increase energy efficiency, new buildings are becoming more airtight. In airtight buildings even slighter imbalances with supply and exhaust airflows can cause high pressure differences. This is why it becomes more crucial in new buildings that the supply and exhaust airflows are actually in balance.

### 3.1.1 Pressure depending system

Pressure depending DCV systems have a mixing box and VAV fans for different zones of the building. The mixing box and fan are linked together with a pressure sensor. The idea is to maintain a constant static pressure within the mixing box (duct static pressure) by increasing or decreasing fan power. (Okochi and Yao, 2016). The system is visualised in Figure 5.

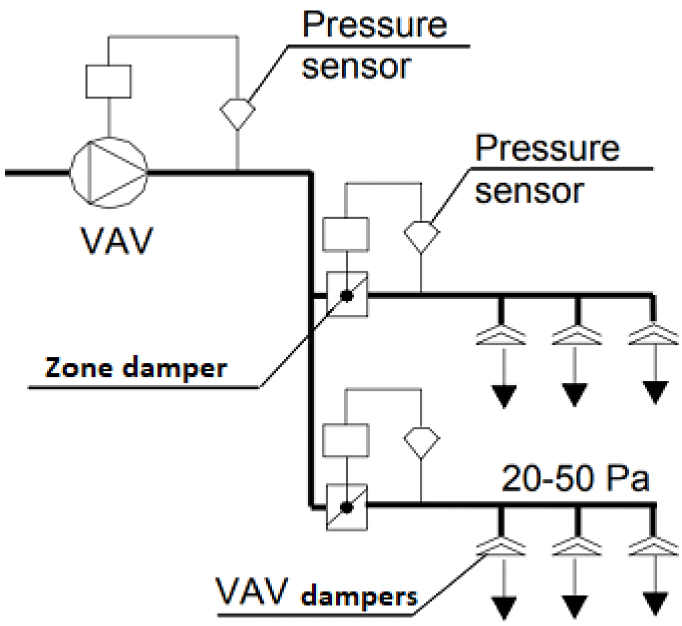


**Figure 5. A layout of a pressure depending DCV system (Maripuu, 2009).**

In a pressure depending DCV system the airflow is adjusted in three different levels, with VAV dampers, zone dampers and the fan. Inside the room, a VAV damper opens or closes to control the airflow, which changes the pressure within the zone duct. The pressure sensor within the zone duct detects the pressure change and starts to control the zone damper to maintain the set duct static pressure. While the zone damper is being adjusted, the pressure sensor after the fan notices a change in the duct static pressure. This forces the fan to either increase or decrease airflow to maintain the set duct static pressure. (Maripuu, 2011)

For a pressure depending DCV system to work, the zone ducts need to be uniform in size. The static pressure in the zone duct is created by static regain phenomena where dynamic pressure is transferred into static pressure. Combined with fairly low air velocity it guarantees that the static pressure remains nearly constant throughout the whole zone duct. The maximum air velocity in the zone duct cannot exceed 3-5 m/s depending on the ventilation system. (*Halton - Vario Design Guide.* 2019)

A more modern way to implement a pressure depending DCV system is with a static pressure reset (SPR) DCV. The main idea of SPR-DCV system is to make sure that the duct static pressure does not increase to higher levels than intended. The system is more complicated and requires more control but when properly functioning it is more energy efficient. In SPR-DCV system all zone dampers are connected to SPR controller. This is shown in Figure 6. The idea is to keep the "critical path's" zone damper position fully open to reduce pressure that decreases fan speed, resulting in lesser energy consumption by keeping the duct static pressure lower, and at the same time satisfying all airflow requirements. The critical path is the duct path with greatest flow resistance. (Schild and Mysen, 2011)

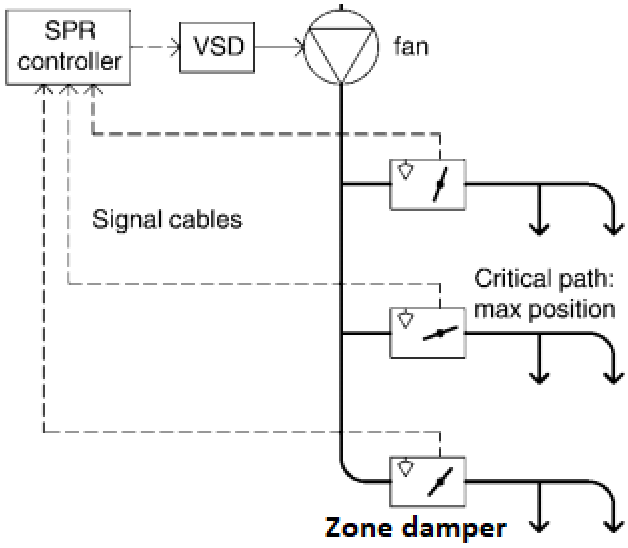


**Figure 6. Ventilation scheme of a SPR-DCV controlled system (Schild and Mysen, 2011).**

The balancing of airflows is important or otherwise the airflows create pressure differences between rooms or over the envelope. The total exhaust airflow needs to be the same as the total supply airflow also within the rooms. With pressure depending DCV systems the exhaust fan is usually set to match the same airflow as the supply fan. One way to balance supply and exhaust airflows is shown in Figure 7. The supply and exhaust dampers are connected as pairs meaning that a supply damper is always connected to an exhaust damper. When a supply damper changes its position the paired exhaust damper also changes its position to match the airflow rates. The zone valves maintain the same supply and airflow rates within the zones.

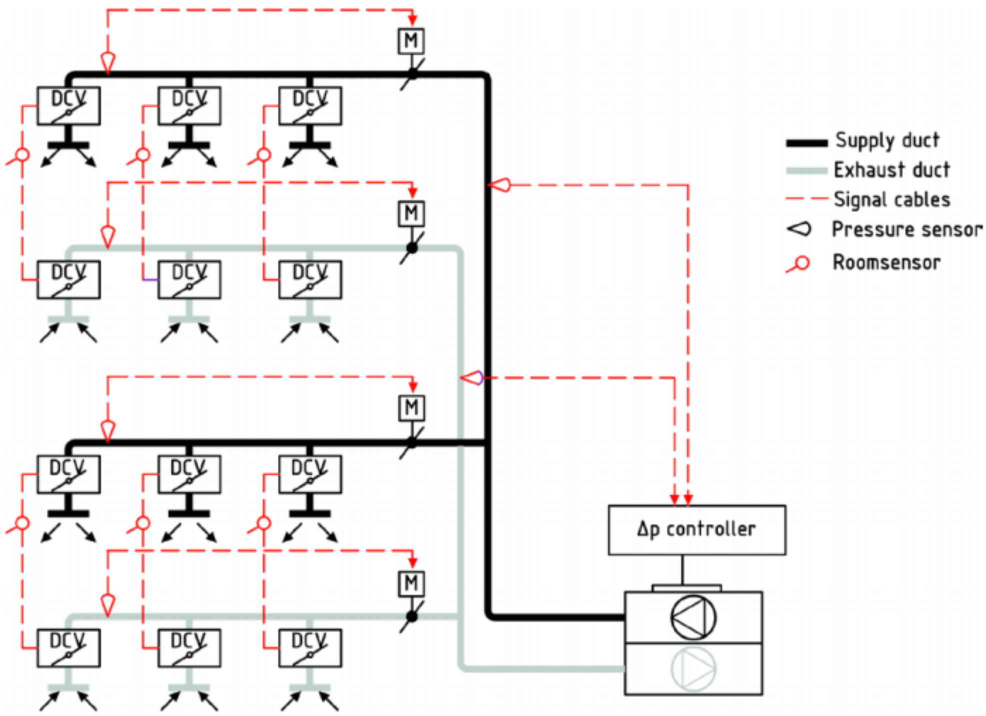


**Figure 7. A layout of pressure depending DCV system with exhaust (Mysen, Schild and Cablé, 2014).**

### 3.1.2 On/off DCV system

A DCV system with on/off dampers is basically a simpler version from a pressure depending DCV system. On/off DCV system works with the same principle as the pressure depending DCV system. The main difference is that in on/off DCV systems the dampers are either fully opened or closed.

For example, an office has two supply air terminals with dampers. The first damper remains constantly open during office hours in order to keep the room ventilated at all times. The other damper opens every time the room's $CO_2$ concentration is above 700 ppm. The ventilation can also be controlled by temperature with or without a $CO_2$ sensor. The room could also have a third supply air terminal unit where the damper opens when $CO_2$ concentration is above 800 ppm for better IAQ control.

The balancing of the supply and exhaust airflows also operate with the same principle as in a pressure depending DCV system but the supply and exhaust dampers are on/off dampers.

### 3.1.3 Pressure independent system

Pressure independent VAV ventilation systems are controlled with VAV room units. A VAV box is located in front of every supply air terminal unit where it measures and controls the airflow. Unlike in pressure depending DCV system, the duct static pressure does not stay constant but changes depending on the controls of VAV boxes. The changes in the duct static pressure need to be compensated in the VAV boxes. Otherwise airflow changes in one room would affect the airflows of neighbouring rooms. Hence, there is less need for zone dampers in the duct system. The control happens by trying to match the duct airflows with the total airflow that is required by the VAV boxes. The pressure independent VAV ventilation system scheme is presented in Figure 8. (Maripuu, 2009)

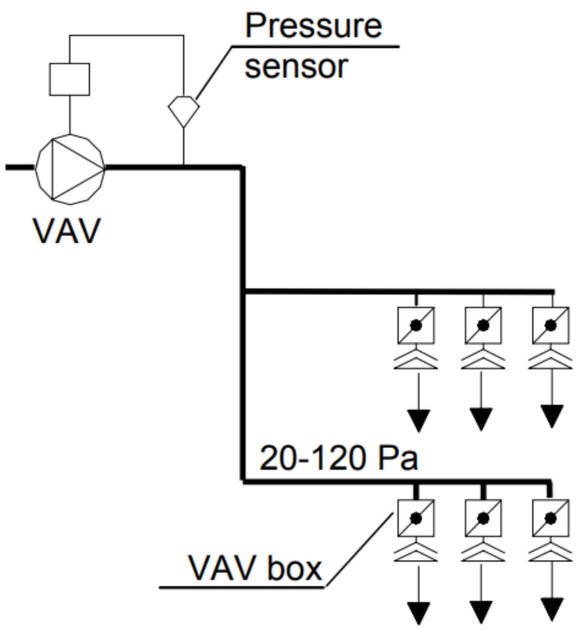


**Figure 8. VAV ventilation system that is controlled with a pressure independent system (Maripuu, 2009).**

With larger systems it is recommended to have a zone damper meaning that there is a damper to control airflows for each branch. The VAV boxes are linked to their own branch controller and the branch controllers are linked to the main controller supply. The zone damper is controlled so that at least one VAV box's damper is in maximally open position. (Mysen, Schild and Cablé, 2014)

One way of balancing a pressure independent DCV system is shown in Figure 9. The total supply and exhaust airflows need to be the same in within the rooms. All supply and exhaust dampers are connected as pairs. When a supply damper changes its position, the paired exhaust damper also changes its position to match the supply airflow. The supply and exhaust fans then need to change the airflow to match the new required total airflows for the rooms. The fans change the pressures within the ducts causing the other dampers to change their position to maintain the required airflows.

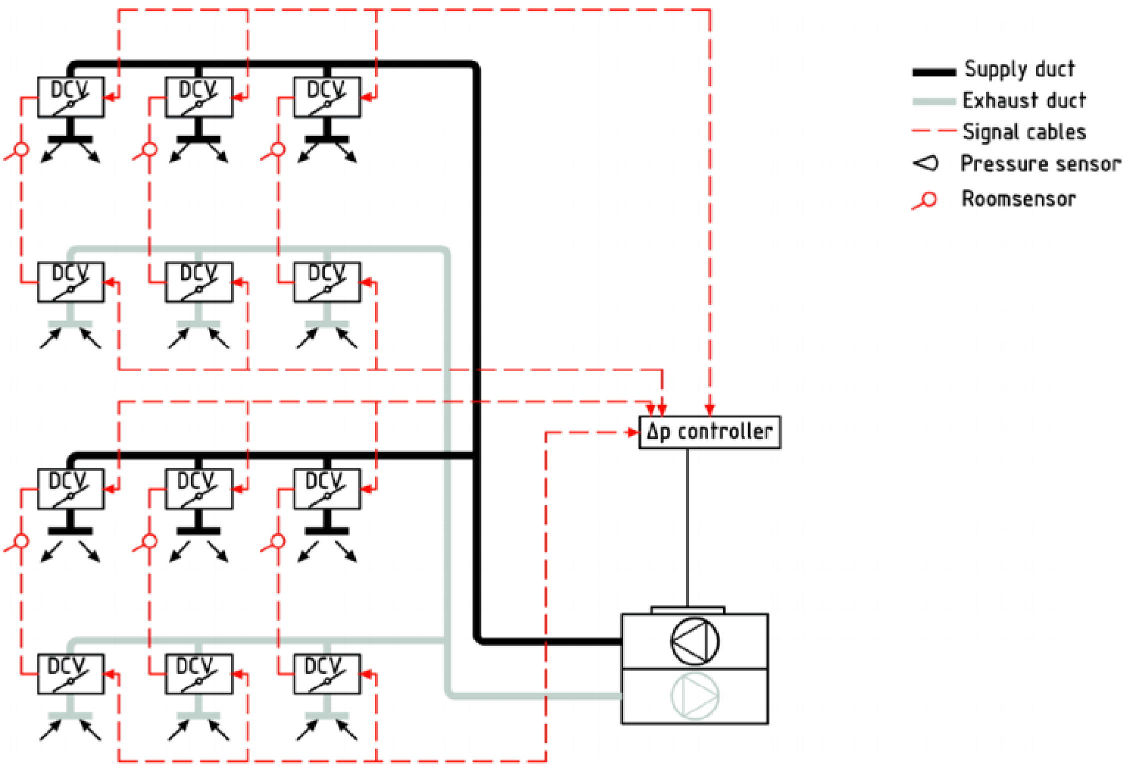


**Figure 9. A layout of a pressure independent DCV system with exhaust (Mysen, Schild and Cablé, 2014).**

## 3.2 Ventilation effectiveness

To maintain good IAQ, the ventilation needs to be effective. Ventilation effectiveness, shown in Figure 10, is defined by its ability to exchange air in the room and to remove air-borne contaminants (Mundt *et al.,* 2004).

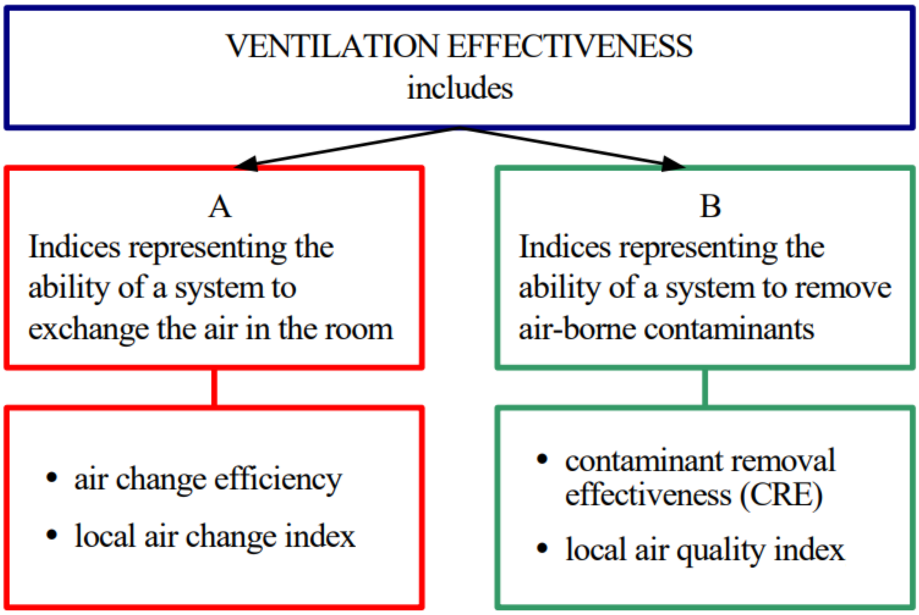


**Figure 10. Factors of ventilation effectiveness** (Mundt *et al.,* 2004)**.**

Air change efficiency (ACE) is 0.5 with perfect mixed flow and 1 with perfect piston flow shown in Figure 11 (Mundt *et al.,* 2004). Contaminant removal effectiveness (CRE) can be infinite if the only contaminant source of the room is at the outlet. With perfect mixed flow CRE is 1. ACE is 0 when the bypass area and recirculation area are completely separated. CRE is 0 in the same scenario when the contaminant source is in the bypass area. Ventilation effectiveness is suitable to measure with ACE when there is no information about an explicit contaminant source. CRE is a better determination for ventilation effectiveness when an explicit contaminant source can be defined. (Novoselac and Srebric, 2003)

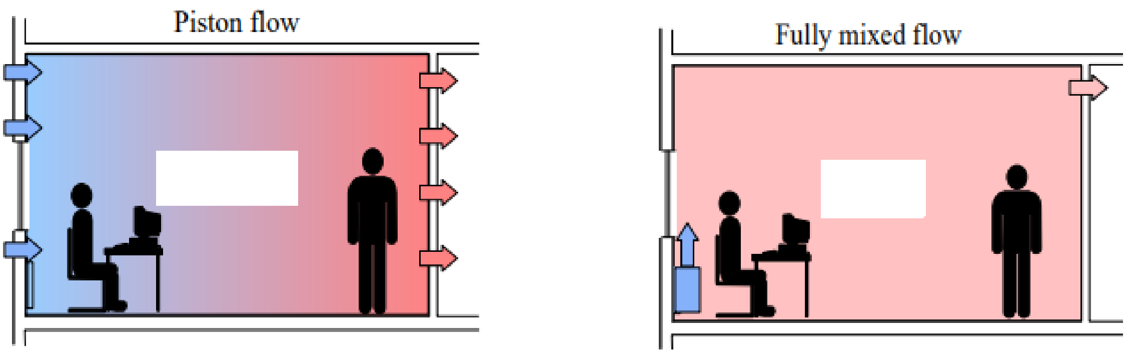


**Figure 11. Piston and fully mixed flow** (Mundt *et al.,* 2004)**.**

## 3.3 Energy efficiency

The main energy savings with VAV systems come from the demand based cooling and heating and the lesser power consumption of the fan compared to a CAV system. With a CAV system the room is most of the time cooled too much which requires the room to be heated to maintain the wanted temperature. This consumes excess energy not only by requiring extra heating to the room, but also simply from over ventilating the room (Maripuu, 2011). This is demonstrated in Figure 12. A VAV system can match the ventilation with cooling demand to save energy. The same principle also works with other parameters ($CO_2$ concentration or occupancy) for VAV ventilation control and a study shows that $CO_2$ controlled VAV system can save up to 51 % energy compared to a CAV system (Merema *et al.,* 2015).

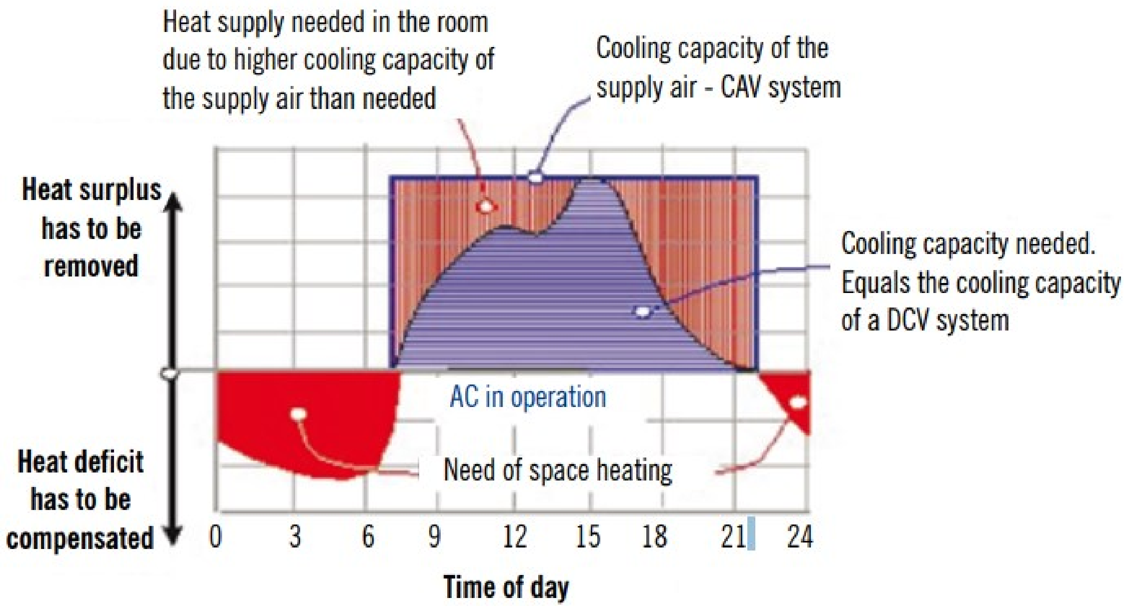


**Figure 12. Heating comparison with CAV ventilation and VAV ventilation (Maripuu, 2011).**

Energy efficiency in all ventilation systems can be increased with a heat recovery system and by recycling exhaust air. Heat recovery systems extract heat from exhaust air to heat new supply air. The Ministry of the Environment states that the heat recovery must be a minimum of 45 % in all new buildings (Energiatehokkuus, 2012). Zero-energy buildings can have a heat recovery system with a yearly efficiency of up to 78 % (Reinikainen, Loisa and Tyni, 2015).

## 3.4 Fault diagnosis

Faults in VAV systems can occur in many different layers but sometimes the problem is somewhere else than in the ventilation system itself. For example, wrong temperature settings on radiators causing them to heat a room too much which the ventilation system is trying to cool leading to waste of energy. Very common reasons for faults are controllers, sensors, subsystems, and components. Detecting faults can lead to energy savings of up to 30 % when comparing with faulty and fully functioning VAV ventilation systems. (Okochi and Yao, 2016)

Most of the time faults with ventilation systems are caused by poor system design, maintenance, application or operation. Faults can be classified as abrupt faults that happen quickly or faults that develop over time. (Okochi and Yao, 2016)

When trying to simulate faults in a DCV system, one way is to use a simulation software tool. A ventilation system can be simulated with different softwares like TRNSYS, ASEAM, BLAST, TAS or TAPP. The simulation can fabricate faults in the ventilation system. Different faults can then be analyzed separately or together. (Liang, Meng and Chang, 2017)

An efficient method to detect faults is studying the trend lines from automation data. Different faults result in different characterized changes within trend lines, which makes certain faults easy to detect. For example, if the room temperature sensor has a positive offset, the supply airflow rate is increased. (Liang, Meng and Chang, 2017)

Also, the energy consumption of the real system and the optimized simulation can be compared at certain points. If the real ventilation system consumes too much or too little energy compared to the simulated ventilation system the ventilation system is not working properly. For example, if the fan supply airflow rate is increased due to a faulty sensor, it can be seen in the energy consumption of the supply fan.

Table 13 shows how different faults affect the ventilation system and room conditions.

**Table 13. Ventilation fault characteristics in five different situations (Liang, Meng and Chang, 2017).**

| Fault | Actual room temperature | Actual supply air temperature | Signal of terminal air valve | Signal of water valve |
|---|---|---|---|---|
| **Positive offset of room temperature sensor** | Low | Unchanged | Increase | Increase |
| **Negative offset of room temperature sensor** | High | Unchanged | Decrease | Decrease |
| **Positive offset of supply air temperature sensor** | Unchanged | Low | Decrease | Increase |
| **Negative offset of exhaust air temperature sensor** | Unchanged | High | Increase | Decrease |
| **Inner surface scaling of the air cooling coils** | Unchanged | Unchanged | Unchanged | Increase |

The ventilation system might not function properly also due to false set point values set in the system for different controllers. For example, if the ventilation and the heating system have both the same set temperature, the heating system is constantly heating the room while the ventilation system is cooling it at the same time. DCV systems can be very energy efficient but if these objectives are not reached due to the complexity of a DCV system, a CAV ventilation system can be a better investment. (Kopra, 2018)

Sometimes, the ventilation system can work perfectly but the IAQ still remains poor. Even if the ventilation system is renewed, the building itself can still have air leakages for example. Older buildings with leakages rarely have bigger pressure differences even though exhaust airflow is usually designed to be higher than supply airflow. In some buildings large amount of bathrooms, kitchens ventilators, fume hoods etc. may lead to higher pressure differences. This is because most of the time when exhaust is intensified supply air should be increased also but most of the systems do not react to intensified exhausts. Even some automated systems react poorly to exhaust boosts. Older buildings have also a lot of single exhausts and their operating time might not match with supply air, which increases pressure differences. Older buildings also have usually more structural problems that cannot be directly connected to the ventilation system. These structural problems can cause air leakages and problems with microbes. It is important to acknowledge that some of the problems that result in poor indoor environment are not always caused by the ventilation system. (Björkroth, Eskola and Rönkkä, 2018)

# 4 Methodology

In this chapter the methodology to analyze the actual performance of VAV ventilation systems is presented. To study the functionality of VAV-systems a single space was selected of each building in the analysis.

The measurements were conducted in eight different public buildings from which six belong to ACRE (Aalto University Campus & Real Estate) and two belong to the city of Helsinki. The selected rooms from these buildings had no known previous diagnosed problems with ventilation or IAQ. In the evaluation of the performance, meeting rooms, classrooms and offices are used in the study. These buildings and rooms are presented in Chapter 5, where all building detailed information can be found.

In all analyzed rooms airflows were measured in normal mode and boost mode. Ventilation is considered to be on normal mode when the space is in normal use and no additional ventilation is demanded. Boost mode is activated when additional ventilation is demanded to the space. Some rooms had a third “unoccupied” mode which was also measured. These measurement results can then be compared to the designed airflow values. Also, a weeklong monitoring measurement period was used for each room for temperature and airflows. These measurements can be used to analyze indoor climate by themselves or compare it to the automation data recorded by the ventilation system.

Before doing any measurements the ventilation drawings were first studied to understand the control strategy of the ventilation system. Every building has a unique ventilation system and therefore different parameters (for example, temperature, $CO_2$ concentration, occupancy, lights) to control the ventilation.

In the research methodology, the ventilation systems were analyzed by using the following phases: first step was to study the design of ventilation systems. Second step was to measure airflows in normal and boost modes and third step was to monitor the performance for one week.

## 4.1 Measurement methods

In every building the performance of ventilation is analyzed by measuring airflows in normal and boost modes. Room air temperatures were measured during a week period. In OIH (Open Innovation House) a monitoring measurement device was left in the room to measure airflow rates continuously for a week. The pressure difference of the room over to hallway or outside air were also measured.

### Selecting rooms

When choosing a room, different types of VAV-ventilation systems were selected. In the tested rooms, the airflow rate is controlled either by occupancy, temperature or air quality.

Automation control strategies are a necessity to compare our measurements with them to assess functionality of the ventilation system.

For practical reasons, offices, meeting rooms and group working spaces were mainly targeted in this study. For that reason, classrooms or lecture halls are not included where the terminal units are at seven-meter height.

Also, for practical reasons it is convenient if the room is easily accessible. Some rooms might be inaccessible and some meeting/group working rooms can be reserved online for measurements, which is convenient.

### Boosting ventilation

The ventilation can be controlled with different sensors and time program depending on the ventilation system. One easy way to control ventilation is with the set time schedule where ventilation airflow rate is reduced outside office hours to save energy. Occupancy detection is possible with occupancy sensors or use of lightings. There can also be room air temperature sensors and VOC or $CO_2$ sensors that can increase ventilation when measured above set levels.

In this study, room specific ventilation is studied and therefore all measurements were inside that room. All the measured rooms had occupancy sensors, room air temperature sensors or $CO_2$ sensors. Most of the rooms had also temperature sensors and $CO_2$ sensors.

In Väre test building, the airflow rate is controlled only with the occupancy sensors. Occupancy sensors react to movement and increase ventilation when detecting someone being present inside the room. During test procedure, the sensor can be blocked with a tape for it to be not able to detect occupancy. The airflows reduce with a delay when the occupancy is not detected.

In this study, $CO_2$ sensors were used to boost ventilation when air quality deteriorates. The space heating is executed with fan coils or radiators. This means that when room air temperature sensors notice an increase in room air temperature, the fan coils or radiators react first and only afterwards the ventilation system starts to increase its airflow. $CO_2$ sensors detect air quality and boost ventilation when the set points exceeded. During the tests, $CO_2$ concentrations were increased by breathing into the sensor.

Some rooms had only room air temperature sensors. For these rooms, a heat gun tool was pointed to the sensor to increase room air temperature. The rooms where this method was used did not have any other reactive ways to control the room air temperature than ventilation.

The ventilation boost works either with steps or the control system modulating airflow rate based on the demand. Airflow working with steps can change the airflow between normal and full boost modes. Relation with the sensors and airflow is shown in Figure 13.

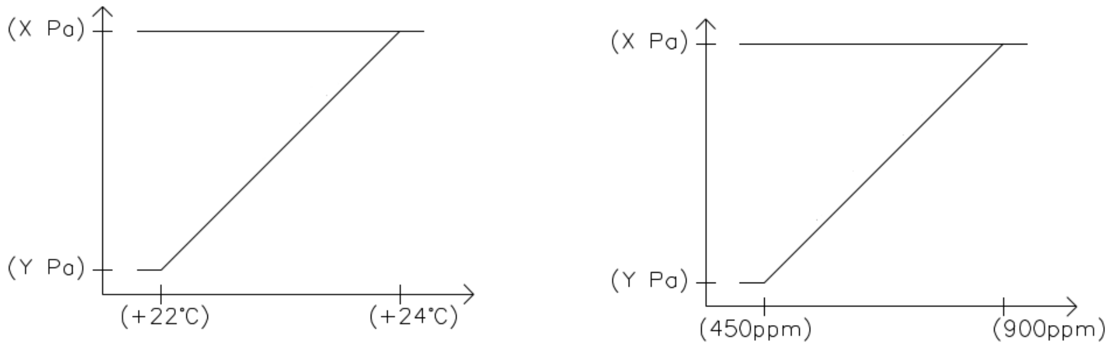


**Figure 13. Ventilation boost with steps. (Y Pa) pressure level indicating normal mode ventilation and (X Pa) pressure level indicating fully boosted ventilation. Ventilation boost reacts to both room air temperature and $CO_2$ concentration.**

In this study, airflows were not measured between normal (Y Pa) and maximum boost mode (X Pa) if boost was stepless. From stepless boosts, the normal and maximum boost modes are tested. Väre had the only room with a third unoccupied mode when the room was empty during the office hours. Unoccupied mode reduces airflow rate below the normal mode set point.

### Monitoring period

In this study, a weeklong monitoring measurement period was used for each room that was being analyzed. The room air temperatures are measured and also the pressure levels of supply air devices with pressure tubes. The pressure levels can be converted to airflows by using manufacture product data.

The monitored measurements were later compared with the automation data. Building management system (BMS) monitors room air temperature, air quality, airflow rates, duct static pressures and damper positions. BMS could be used together with data logger measurements.

### Automation data

All the VAV-systems in this study have an option to measure automation data from sensors. This means that the sensor's measurements are recorded to a computer from where they can be viewed or extracted later. Unfortunately with most systems, automation data has not been recorded.

Analyzing room conditions is easier with automation data since it is possible to compare measurement results with the system's measurements. Also, simply looking at the automation data can show if a room's ventilation is working properly or not. For example, if a room has constantly too high temperature, boost mode on, or too high $CO_2$ concentration something is not working properly.

### Measurements

Different measuring methods were used in different rooms. Airflow measurements (normal and boost mode) and temperature monitoring measurements were done in each room. Studied terminal units need to be measured in different ways and monitoring pressure difference measurements can only be done if there are pressure tubes available and a good location for the measurement device in order to leave it for the measurement period. Therefore, different devices were used in different rooms and pressure difference monitoring measurements could only be done in OIH (Open Innovation House). The measurement instruments mentioned in Table 14 are presented in Chapter 3.2.

### Selected methods

Presented methods were chosen because multiple buildings needed to be analyzed in a short time frame. One objective of this study is to introduce a quick and easy method to determine the performance of ventilation system. One way to do this is to address functionality by measuring airflows and comparing them to the designed values. A weeklong monitoring period is an easy way to figure out how the room air temperature and airflows change during time. The monitoring measurements can also be compared against automation data to find out whether the ventilation system is working as designed.

Functionality can also be addressed with more detailed measurements in all different scenarios of the ventilation systems to find out exactly how the ventilation systems works and comparing it to how the ventilation system is designed to work. A method like this gives more specific information about the ventilation system but also requires a lot more time and resources. This sort of method is too excessive if the objective is simply determining the functionality of the ventilation system without a necessity for excess information.

Table 14. Room specific measurements, used devices and BMS data.

| Building Room | Measured parameters | Measurement instruments used | Collected data from building management system (BMS) |
|---|---|---|---|
| Dipoli<br>2.062 | - Airflows<br>- Temperature monitoring | - LCA 6000 + horn<br>- Swema 3000<br>- TinyTag 2 | - Exhaust duct static pressure<br>- Supply duct static pressure<br>- Exhaust air temperature |
| Väre<br>R307/R310 | - Airflows<br>- Temperature monitoring | - LCA 6000 + horn<br>- TinyTag 2 | - Room air temperature<br>- Supply duct static pressure<br>- Exhaust duct static pressure |
| Otakaari 1<br>U106 | - Airflows<br>- Temperature monitoring | - Swema 3000<br>- Testo 435 + horn<br>- TinyTag 2 | - Room air temperature<br>- Room $CO_2$ concentration<br>- Room damper positions |
| OIH<br>B205 | - Airflows<br>- Temperature monitoring<br>- Pressure difference monitoring | - Swema 3000<br>- LCA 6000 + horn<br>- TinyTag 2<br>- Sensirion SDP816 | No data available |
| TUAS<br>2104 | - Airflows<br>- Temperature monitoring | - Swema 3000<br>- LCA 6000 + horn<br>- TinyTag 2 | No data available |
| Learning Centre<br>136 | - Airflows<br>- Temperature monitoring | - Swema 3000<br>- TinyTag 2 | No data available |
| School in Helsinki<br>221 | - Airflows<br>- Temperature monitoring | - Swema 3000<br>- LCA 6000 + horn<br>- TinyTag 2 | No data available |
| Vocational school | - Airflows<br>- Temperature monitoring | - Swema 3000<br>- TinyTag 2 | - Room air temperature<br>- Room damper positions |

## 4.2 Measurement instruments

### Airflow rates

In this study four different devices were used to measure airflow rate: one Manometer and three Anemometers. Technical specifications for the airflow measuring devices are presented in Table 15.

Table 15. Technical specifications of the instruments.

| | Swema 3000 | LCA 6000 | Testo 435 | Velocicalc 8388 |
|---|---|---|---|---|
| Operating temperature | 0 to +50 ºC | -10 to +50 ºC | -20 to +50 ºC | -10 to +60 ºC |
| Measuring range | -300 to 1500 Pa | 0.25 to 30 m/s | 0.6 to 40 m/s | 0.15 to 50 m/s |
| Max Load | ±50000 Pa | - | - | - |
| Accuracy | ±0.3 % from read value, ±0.3 Pa | ±0.1 m/s (from 0.25 to 4.99 m/s)<br>±2 % (from 5 to 30 m/s) | **±1.5 % from read value, ±0.2 m/s** | ±3 % from read value, ±0.02 m/s |
| Temperature dependency | 0.2 Pa/ºC | - | - | - |
| Resolution | | 0.01 m/s | 0.1 m/s | **0.01 m/s** |
| Vane diameter | - | - | 16 mm | - |

Manometer Swema 3000 md was used to measure pressure differences. Airflows are calculated by using pressure differences and product data. Most of the terminal units have pressure tubes that can be connected to Swema 3000 or any other similar device. These pressure tubes are shown in Figure 14. The pressure differences can be converted to airflow q [l/s] with following equation:

$$q = k\sqrt{\Delta Pa} \tag{1}$$

Where q is airflow [l/s], k is product specific factor and ΔPa is the pressure difference. The k-factor depends on terminal unit's model and can be found from the terminal unit manual.

**Figure 14. Terminal unit with pressure tubes. The tubes are folded on the grille for easy measurements.**

Swema 3000 was also used to measure pressure differences over the room to outdoor or surrounding areas e.g. corridor.

In this study, three different anemometers were used: TSI Airflow LCA 6000, Testo 435 and TSI Velocicalc 8388. Technical specifications of the measurement devices are presented in Table 15. LCA 6000 was mostly used to measure the exhaust airflows, Testo 435 was used once in Dipoli to verify measurements with manometer Swema 3000. Verifications for Swema 3000's measurements are required when the diffuser has too low airflows for its dimensioning. This results in unreliable measurement results since slight changes in the pressure can change the calculated airflow massively. Velocicalc was used to calculate supply airflow in Väre since the supply diffuser had no pressure tube connections. All these measurement instruments are presented in Figure 15.


**Figure 15. The used measurement instruments**

LCA 6000 was used with an airflow horn to measure airflows. Anemometer and airflow horn were only used to measure exhaust airflows. Most of the exhaust outlets were same sized (D=160) valves that is shown in Figure 16. The black airflow horn (see Figure 15) suits to measure them. To measure airflow, the horn was tightly placed around the valve so that all air flows through the anemometer. The anemometer is set to measure for approximately 10 seconds and it calculates automatically the average airflow of the measured time.

**Figure 16. Exhaust air valves with diameter of D=160.**

Testo 435 was also used to measure airflows with a Wallac AM-1200 airflow horn and it was only used in Dipoli. Unlike with LCA 600 where the device calculates the airflow automatically, the airflow q [l/s] is calculated with following equation:

$$q = 100v \tag{2}$$

Where $v$ is air flow speed [m/s].

In multi-spot method the flow speeds are measured from different spots of the air device according its geometry. Also, the area where the air flows needs to be measured. The airflow q [l/s] is calculated with following equation:

$$q = 1000\frac{x_1 + \cdots + x_n}{n} * A \tag{3}$$

Where $\frac{x_1+\cdots+x_n}{n}$ is the arithmetic average of the flow speed measurements and $A$ is the area.

Factory calibration was still valid for Swema 3000. LCA 6000, Velocicalc 8388 and Testo 435 has been cross calibrated with other instruments so that the measurement results do not deviate a lot from reality.

### Loggers

In this study, two different loggers were used. Loggers measured temperature and pressure differences and they are shown in Figure 17. Loggers were used to measure rooms for a week period. Technical specifications for logger devices be found in Table 16.

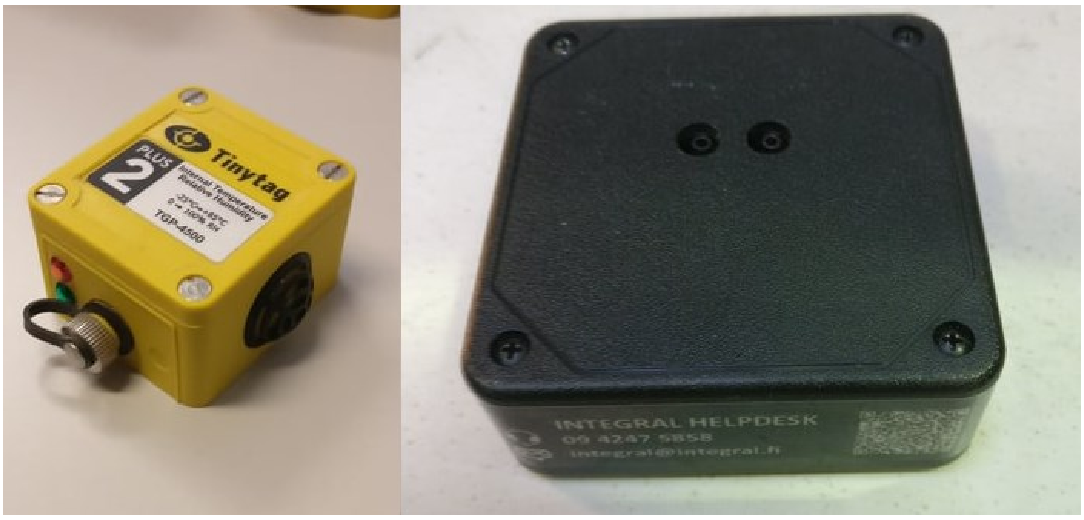


**Figure 17. TinyTag 2 plus TGP on the left side and Sensirion SDP816-125Pa on the right.**

TinyTag 2 plus TGP 4500s were used to monitor room air temperatures. It was usually placed at 1 m height from the floor level and central location of the room. Corners, windows, radiators, exhaust and supply air devices were avoided to get proper data.

Sensirion SDP816-125Pa's were used to measure pressure differences. Sensirions were connected to terminal unit's pressure tubes to measure pressure differences. These measured pressure differences can be converted to airflows when the k-factor is known.

**Table 16. Technical information of temperature logger TinyTag 2 plus TGP 4500 and pressure difference logger Sensirion SDP816-125 Pa.**

| | TinyTag 2 plus TGP 4500 | Sensirion SDP816-125Pa |
|---|---|---|
| Operating temperature | -25 ºC to +85 ºC | -25 ºC to +85 ºC |
| Measuring range | - | ±0.125 kPa |
| Max Load | - | 100 000 kPa |
| Accuracy | ±3 % | ±3 % |
| Resolution | 0.01 ºC | 0.1 Pa |

Factory calibration was still effective for Sensirions. TinyTags were calibrated in a laboratory environment.

# 5 Results

In every test room, the performance of ventilation was tested in normal mode and boost modes. Additionally, measurements were executed to monitor temperature and pressure differences of supply air devices over a one-week period.

Basic information about the buildings and the ventilation systems are presented in Table 17. Most of the buildings have a new or lately renovated DCV system. In a pressure depending ventilation system the supply duct static pressure is a constant. On/Off dampers can either fully open or fully close and stepless dampers can do the same and everything between fully opening and closing.

**Table 17. The buildings and their ventilation systems.**

| Building | Owner | Building size [m2] | Built in / Renovated in | Ventilation system | Damper control |
|---|---|---|---|---|---|
| Dipoli | ACRE | 10828 | 1966 / 2017 | Pressure depending | On/Off |
| Väre | ACRE | 47500 | 2018 | Pressure depending | Stepless |
| Otakaari 1 | ACRE | 48000 | 1965 / 2015 | Pressure depending | On/Off |
| OIH | ACRE | 11600 | 2012 | Pressure depending | Stepless |
| Learning Centre | ACRE | 25000 | 1969 / 2016 | Pressure depending | On/Off |
| TUAS | ACRE | 18000 | 2003 | Pressure depending | Stepless |
| School in Helsinki | City of Helsinki | 3109 | 1942 / 2016 | Pressure depending | Stepless |
| Vocational school | City of Helsinki | 11836 | 1968 / 2014 | Pressure depending | Stepless |

In this study, one room for each of the eight buildings chosen for the sample were studied. The selected rooms in the buildings are shown in Table 18.

**Table 18. The analyzed buildings and rooms.**

| Building | End user | Selected room | Type of room |
|---|---|---|---|
| Dipoli | Aalto University main building | 2.062 | Meeting room |
| Väre | Main building for Aalto School of Arts, Design and Architecture | R312 | Office |
| Otakaari 1 | Aalto University Undergraduate Centre | U106 | Group working space |
| OIH | High school and office building | B205 | Meeting room |
| TUAS | Aalto School of Science and Aalto School of Electrical Engineering | 2104 | Meeting room |
| Learning Centre | Library and study spaces | 136 | Office |
| School in Helsinki | School of visual arts | 221 | Class room |
| Vocational school | Vocational school | 2027 | Class room |

## 5.1 Dipoli

Dipoli is a building in Otaniemi campus (Otakaari 24, Espoo) owned by ACRE. It was first built for student union of Helsinki University of Technology, but it was bought by Aalto University in 2013. Now it is the main building of Aalto University and it operates as a multipurpose building. Dipoli has work spaces, space for venues, exhibition spaces, and restaurants. Dipoli had extensive renovation during 2015-2017 when the ventilation system was upgraded to fulfil the demands of the existing building code.

**Figure 18. Dipoli the main building of Aalto University.**

From Dipoli, room 2.062 was selected for the analysis. The room is a meeting room for employees of Aalto University. All required documents were available regarding airflow rates and control strategy of ventilation system. The documents did not include the exact information about the models of terminal units.

### Ventilation system

The AHU ventilates room 2.062. The AHU also serves two other smaller meeting rooms and the dining area in Dipoli, but only the test room 2.062 and the food service area have a VAV-system. Figure 19 shows the ventilation design for the test room 2.062. The room has two supply air diffusers, two exhaust air valves, two dampers and two fan coils. The fan coils recycle the room air without any outdoor air connection and they control only the room air temperature. One of the two supply air devices is controlled with a damper, same goes for the relevant exhaust air device. The dampers control airflows based on temperature and $CO_2$ concentration. The exhaust air damper is marked FG17.2 and supply air damper FG15.2 in Figure 17. Combination of the dampers is called damper pair FG.

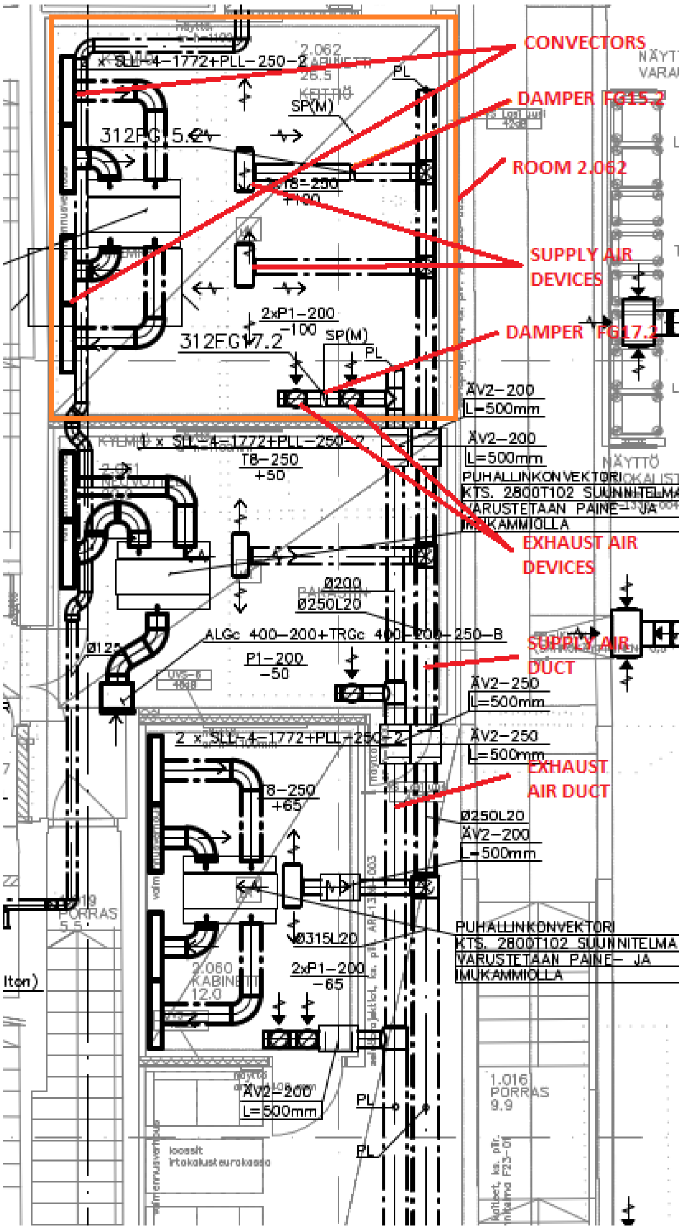

Figure 19. Ventilation design of room 2.062 in Dipoli.

### Ventilation automation

There are two parameters that influence airflows for the room 2.062: duct static pressure control and damper opening. The supply and exhaust duct static pressures of the AHU are controlled by room air temperature and $CO_2$ concentration. The duct static pressure can vary between normal mode (75 %) and boost mode (75-100 %). The duct supply and exhaust static pressure sensors are inside the AHU or close to the AHU in the duct. The dampers are controlled with $CO_2$ and temperature sensors within the room.

The AHU has only one temperature sensor to control duct static pressures. The temperature sensor (TE19) is located inside the AHU or inside the duct close to it. The sensor increases both supply duct static pressure and exhaust duct with same relation that is shown in Figure 20. Minimum (Y Pa) and maximum (X Pa) pressure values are not specified in ventilation drawings but automation data Figure 23 indicates that the supply duct static pressure (Y Pa) is 180 Pa and the exhaust duct static pressure (Y Pa) is 320 Pa. Every time the exhaust air temperature sensor measures a temperature over 22 ºC the duct static pressures increase and the duct static pressures are at 100 % when the exhaust air temperature is at or above 24 ºC.

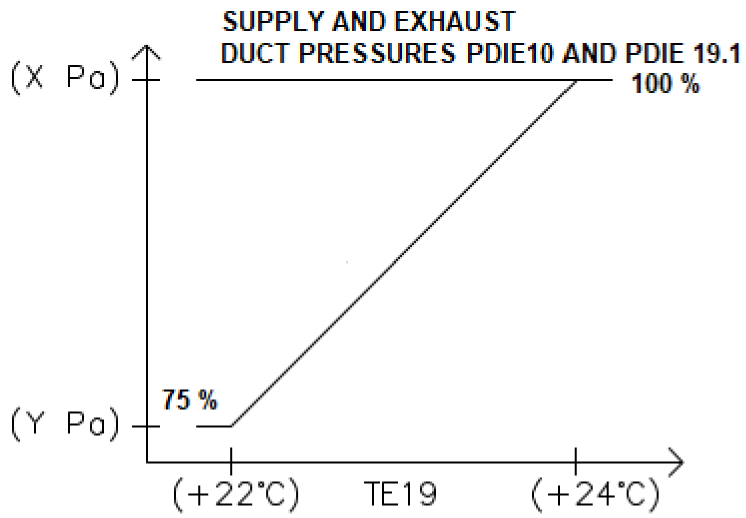


**Figure 20. Temperature sensor in exhaust duct controlling AHU's supply and exhaust duct static pressures.**

The AHU's duct static pressures are also controlled by six different $CO_2$ sensors (QE/TE16.X). The $CO_2$ sensors are located inside room 2.062 and the food service area. If any of the measured value of $CO_2$ concentration is with too high concentration, the duct static pressures are increased. The increased duct static pressures are different for supply and exhaust depending on $CO_2$ concentrations and they are shown in Figure 21. Supply duct static pressure is increased at 450 ppm and exhaust duct static pressure at 600 ppm and at 900 ppm both duct static pressure are at 100 % (X Pa).

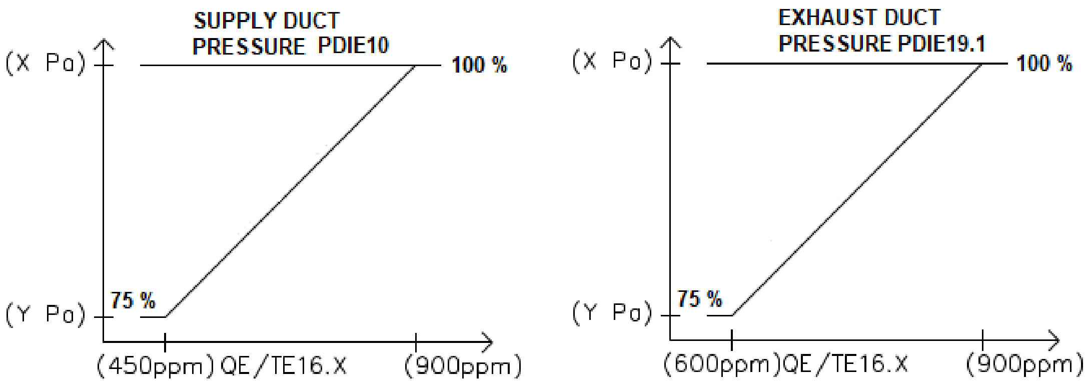


**Figure 21. $CO_2$ sensors controlling the AHU supply and exhaust duct static pressures.**

The only dampers that can be controlled by the ventilation automation system connected to the AHU is damper pair FG. The dampers are on/off dampers so they are either fully closed or fully open. Both of dampers are inside room 2.062. Other damper controls the airflow for supply air device and the other damper controls the airflow for other exhaust air device. In the normal mode, the dampers are closed and thus, there is only one exhaust air device and one supply air device open. Both dampers open when the room $CO_2$ sensor detects $CO_2$ concentrations surpassing the set $CO_2$ concentration. This means that the supply and exhaust airflow are approximately doubled.

The supply air temperature (TE10) depends on the average exhaust air temperature (TE19). When the exhaust air temperature rises, supply air temperature is lowered. The correlation between supply air temperature set value and exhaust air temperature is shown in Figure 22.

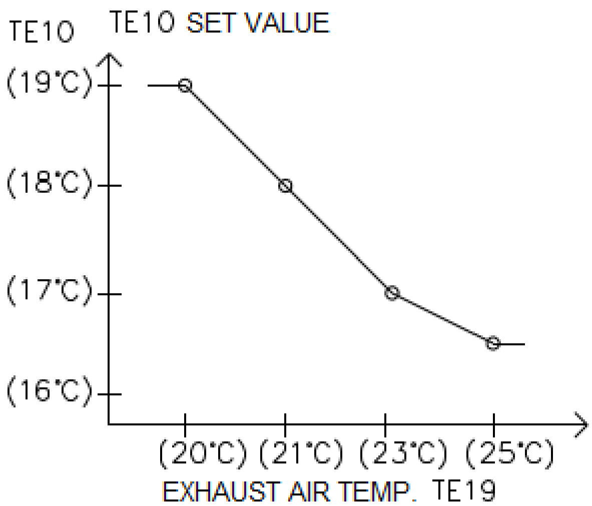


**Figure 22. Supply air temperature set value depends on exhaust air temperature.**

### Measured airflow rates

Room 2.062 has two same size of supply air and two exhaust air devices. The measurements were done in the normal and boost modes (100 %). The results are presented in Table 19.

**Table 19. Measurement results for Dipoli room 2.062.**

| Mode | Supply airflow [l/s] | | Exhaust airflow [l/s] | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|
| | **Measured** | Design | **Measured** | Design | | |
| **Normal** | **118** | 50 | **33** | 50 | **86** | **361** |
| **Boosted** | **81** | 100 | **24** | 100 | **57** | **336** |

In the normal mode, the room has a very high supply airflow and it is 3.6 times greater than the exhaust airflow. The high airflows in the normal mode are because the damper pair FG is open. In the normal mode, these dampers should be closed.

In the boost mode, the airflow decreases compared to normal mode. This is because damper pair FG that should be open is now closed. Also, in this case, the supply airflow is now 3.4 times higher than the exhaust airflow.

It is obvious that the ventilation does not work properly in room 2.062. The supply/exhaust airflow ratios are way too high in normal and boost mode and the airflows do not match the designed values.

### Monitoring measurements

Monitoring measurement were done for temperature levels with a TinyTag in room 2.062. There was not any suitable place in the ceiling for pressure difference monitoring of supply air devices. Automation data was available for AHU's supply duct static pressure, exhaust duct static pressure and exhaust air temperature. Data was not available for damper positions in the room 2.062 nor for the $CO_2$ sensors. Measurements from TinyTag and ventilation sensors are shown in Figure 23. Duct static pressures depend on exhaust air temperature (Figure 20) and $CO_2$ concentrations measured by the $CO_2$ sensors (Figure 21).

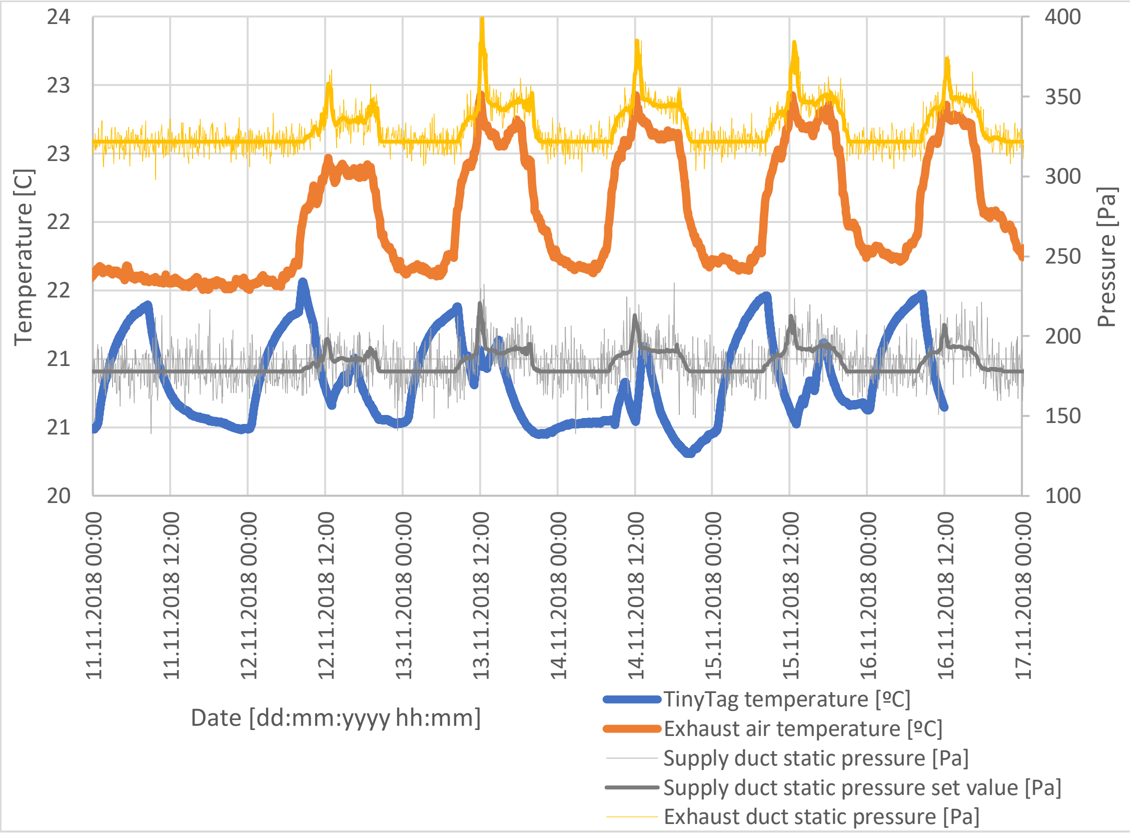


**Figure 23. Temperature monitoring measurements compared to the AHU automation data.**

From Figure 23, it can be observed that the TinyTag temperature measurement follows a similar pattern to AHU's exhaust air temperature. The TinyTag temperature varies approximately between 20.5-21.5 ºC, which within inside the designed boundaries. The temperature measurements do not correlate perfectly with each other because the TinyTag measured temperature only from room 2.062 and the exhaust air temperature sensor measures the overall exhaust air temperature of the AHU.

Figure 23 indicates that in normal mode the set supply duct static pressure (Y Pa) is 180 Pa and the set exhaust duct static pressure (Y Pa) is 320 Pa but the maximum duct static pressures (X Pa) for supply and exhaust ducts never reached the set point. According to ventilation design $CO_2$ concentration the supply and exhaust duct correlate with each other at all times excluding when $CO_2$-sensors detect 450-600 ppm (shown in Figure 21) when only supply air duct static pressure is increased. It remains unknown how the duct static pressures react to $CO_2$ concentration since there are no automation data by $CO_2$ sensor.

Figure 23 shows that immediately when the exhaust air temperature sensor measures temperature of 22 ºC the duct static pressures increase as designed according to automation drawings. Since temperature measured by the exhaust air temperature sensor never exceeds 24 ºC the 100 % duct static pressure (X Pa) remains unknown.

The AHU duct static pressure reacts properly to temperature measured by the exhaust air temperature sensor. Every time the sensor measures temperature over 22 ºC duct static pressures are increased as designed. Also, the correlation between temperature measurements (TinyTag and the exhaust air temperature sensor) is obvious. It is also not possible to say how the dampers in room 2.062 react to $CO_2$ concentrations measured inside the room in a longer time period since there is no automation data recorded from damper positions nor $CO_2$ concentrations.

### Conclusion

Ventilation boost and normal mode do not work properly in room 2.062. Damper pair FG reacts to increased $CO_2$ concentrations as they should, but they work exactly the opposite way they are intended to operate. The boosting dampers are open in the normal mode and closed in the boost mode. The dampers should be closed in normal mode and open in boost mode. This is because of a fault made in the installation phase of the dampers. Despite this, the indoor air conditions in the room are good meaning that simply studying room conditions the functionality of ventilation cannot be defined.

That is leading to the situation that the supply air and exhaust air ratio is in normal and boost mode over 3. This means that there are over 3 times more supply air than exhaust air. When the door is closed, this leads excess pressure inside the room over the envelope and surrounding area and it might affect the difficulty to close the door.

The room air temperature stays within the designed boundaries. The room air temperature stays approximately between 20.5-21.5 ºC never exceeding 22 ºC. When the exhaust air temperature for the AHU exceeds 22 ºC, duct static pressures increase. The duct static pressures react properly increasing duct static pressure every time exhaust air temperature exceeds 22 ºC and otherwise remain at the set standard levels.

Automation data about the $CO_2$ sensor QE/TE16.X or dampers FG17.2 and FG15.2 was unavailable and therefore it is impossible to say how these dampers and duct static pressures react to $CO_2$ concentration.

All the necessary ventilation drawings about the control strategy of ventilation were available.

## 5.2 Väre

Väre is a building in Otaniemi campus (Otaniementie 14, Espoo) owned by ACRE. It is a new main building for Aalto School of Arts, Design and Architecture finished in 2018. Väre has spaces for the staff (offices for professors, researchers etc.), lectures and students. Besides the School spaces, it also has a shopping center (A bloc) and a metro station. Shopping center consists of restaurants, gym, food stores, cafeterias and few other service providers. Väre also has spaces for Aalto School of Business. Väre is 90 % self-sustainable utilizing geothermal energy and solar panels.


**Figure 24. Väre the main building for School of Arts, Design and Architecture.**

Rooms R307 and R310 were chosen for analysis from Väre. The rooms work as a one-person office rooms for researchers. The rooms' layouts and ventilation systems are identical in all offices R304-R313. The airflow measurements were done in room R307 because it was not in active use. The monitoring measurements were done in room R310 to receive measurement data from a room that occupied. Ventilation drawings were not complete lacking information about AHUs and types of supply air devices for selected room.

### Ventilation system

The AHU ventilates eight identical offices R304-R313 that are next to each other and including other areas on different levels of the building. Figure 25 shows ventilation design for the room R307. Each room has one supply air and exhaust air device and two dampers. Supply airflow is controlled with the dampers that are named MVIS15.R3.05 for supply air MVIS17.R3.05 for exhaust air. The room also has a radiant panel connected to cooling valves that is not shown in Figure 25.

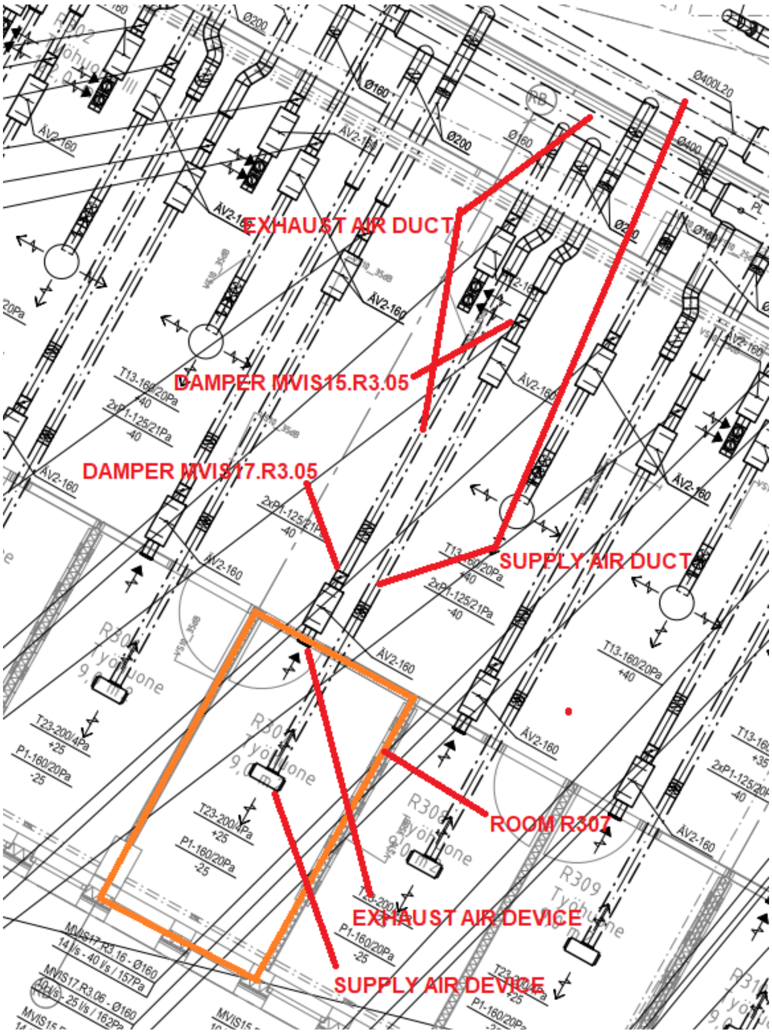

**Figure 25. Ventilation design of room R307 in Väre.**

### Ventilation automation

The ventilation is controlled with room air temperature sensors and lightings (occupancy). Lightings are sending messages to the ventilation system that the room is occupied when lightings are on and unoccupied when lightings are off. Automation design drawings state that the lightings also control ventilation this way, but this was proven wrong in field tests. In reality, the room has occupancy sensors to which the ventilation system reacts instead of lightings.

Rooms R304-R313 have 3 different operation modes in ventilation: minimum, normal, and boost modes. When occupants are not detected ventilation is on minimum mode where the airflow rate is 25 % of the maximum airflow. When occupancy is detected, ventilation turns on to the normal mode which is 66 % of the maximum airflow. The temperature is controlled primarily with cooling valves. If the cooling from cooling panels is not sufficient and the temperature rises above a set temperature (for example 25 ºC), ventilation starts the boost mode which is 100 % of the maximum airflow. Airflow returns to normal mode from boost mode when the temperature decreases over 1 ºC from the set boosting temperature. Operation modes change in steps, so the airflow does not change linearly between the steps. The room airflows are controlled with the room specific dampers.

The room air temperature is set on a level that depends on outside air temperature. Room air temperature is primarily controlled with cooling panels and secondary on ventilation. In Figure 26 is shown the relationship between outside air temperature and room air temperature. The minimum room air temperature is 21 ºC when outside air temperature is at 12 ºC and the maximum room air temperature is 24 ºC when outside air temperature is at 22 ºC. When the room is unoccupied the set room air temperature is increased by 1 ºC and when the room has been unoccupied for 48 hours the set room air temperature is increased by 2 ºC (shown in Figure 26).

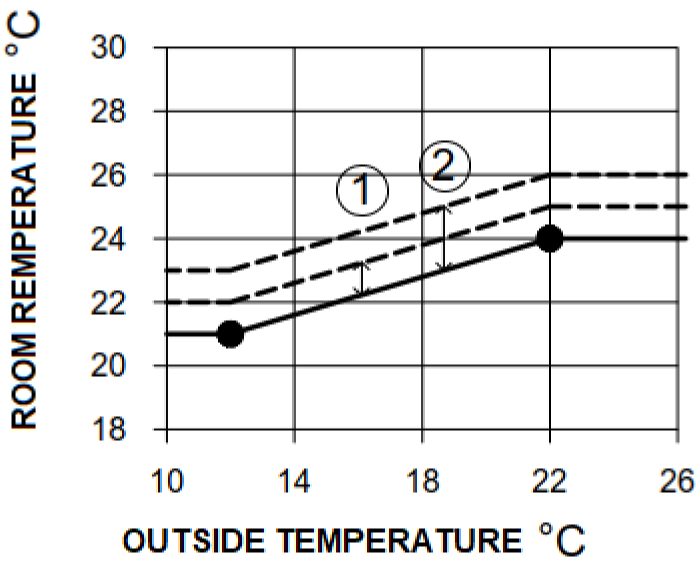


**Figure 26. The room air temperature set point as a function of outside air temperature. Diagram 1 is used when unoccupied mode and diagram 2 after being 48 hours unoccupied.**

The supply air temperature depends on outside air temperature. When outside air is 21 ºC or lower the supply air temperature is 18 ºC. When outside air is 25 ºC or higher the supply air temperature is 16 ºC. The supply air temperature changes linearly between 16-18 ºC when the outside air is 21-25 ºC which is shown in Figure 27.

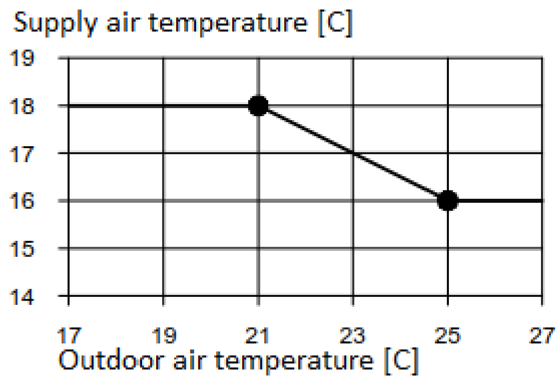


**Figure 27. Supply air temperature.**

### Measured airflow rates

Supply air device was connected to Halton Ava AVP radiant panel. This was designed so that part of the supply air flowed on top the panel and only part of the airflow came through the grille. The supply diffuser did not have pressure tubes, so airflows should be measured with an airflow horn or multipoint method. The supply airflow measurements were not reliable even when measured with the previous methods since part of the airflow was directed on top of the radiant panel.

Because the airflows could not be measured manually, the airflows were converted from damper positions. The dampers are TROX VFC 160 dampers. The airflows depend on damper positions and the relation is shown in Figure 28. The volume flow controller keeps a variable set flow rate constant independently of the duct pressure. The differential pressure needs to be 30-500 Pa.

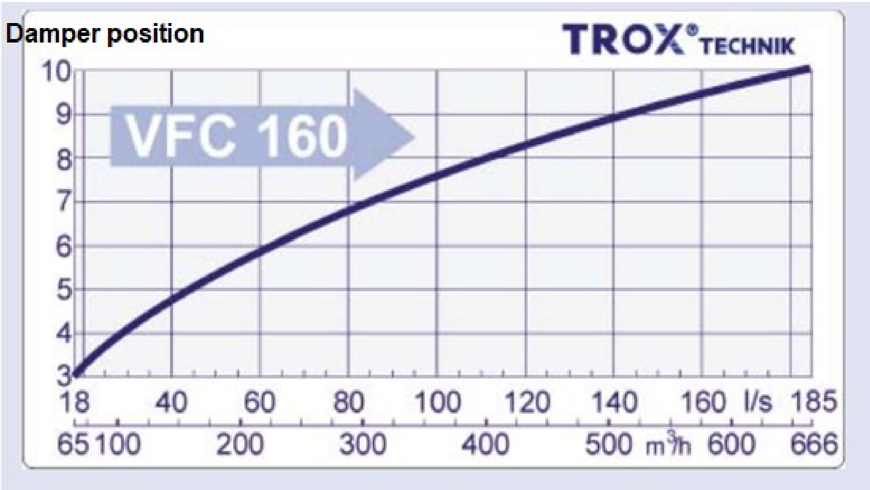


**Figure 28. TROX VFC 160 dampers' airflows on different damper positions when the differential pressure is 30-500 Pa.**

In the field test, the minimum mode was achieved by blocking the occupancy sensor, normal mode just by being in the room and letting the occupancy sensor detect occupancy, and boost mode by using a heat gun to blow warm air to the temperature sensor. The damper positions for each mode and airflows are shown in Table 20. The damper is fully opened in position 10. As it is shown in Figure 28, a damper position under 3 is outside the measurement range.

Table 20. Damper position and airflows for room R307.

| | Supply airflow | | | Exhaust airflow | | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|---|---|
| | Damper position | Airflow [l/s] | Design [l/s] | Damper position | Airflow [l/s] | Design [l/s] | | |
| Minimum | 1.3 | Outside measuring range | 6 | 1.0 | <16 | 6 | N/A | N/A |
| Normal | 3.4 | 22 | 17 | 2.7 | 16 | 17 | 5 | 138 |
| Boost | 4.2 | 30 | 25 | 3.4 | 25 | 25 | 5 | 120 |

In the minimum mode, the damper position for supply air is 1.3 and exhaust air 1. The corresponding airflows are not available in Figure 28 being outside the measurement range.

In normal and boost mode the exhaust airflows are very close to the designed values, but the supply airflows are not.

The room has higher supply airflow compared to exhaust airflow which results in excess pressure. The ratio between the airflows is high and can cause high pressure difference over the envelope and surrounding area.

### Monitoring measurements

Monitoring measurement was conducted for room air temperature levels with TinyTag in the room R310. The supply air devices did not have pressure tubes hence monitoring measurements for pressure differences were not performed. Following automation data was available: R310 the room air temperature, supply duct static pressure and exhaust duct static pressure for the AHU. Data was not available for control damper positions.

The room air temperature stays within the designed boundaries. Figure 29 shows that TinyTag temperature measurement is similar to the room's temperature sensor. The temperature changes are reasonable between 20.5-22.5 ºC measured by the room's temperature sensor with the room air temperature very rarely exceeding 22 ºC staying within the designed values. TinyTag measurements has a few higher spikes that can be due to the sensor being located on the office desk. In Figure 29 dates 2.12 and 3.12 are Saturday and Sunday where it can clearly be seen that the temperature remains less volatile for those dates indicating that the room has been empty.

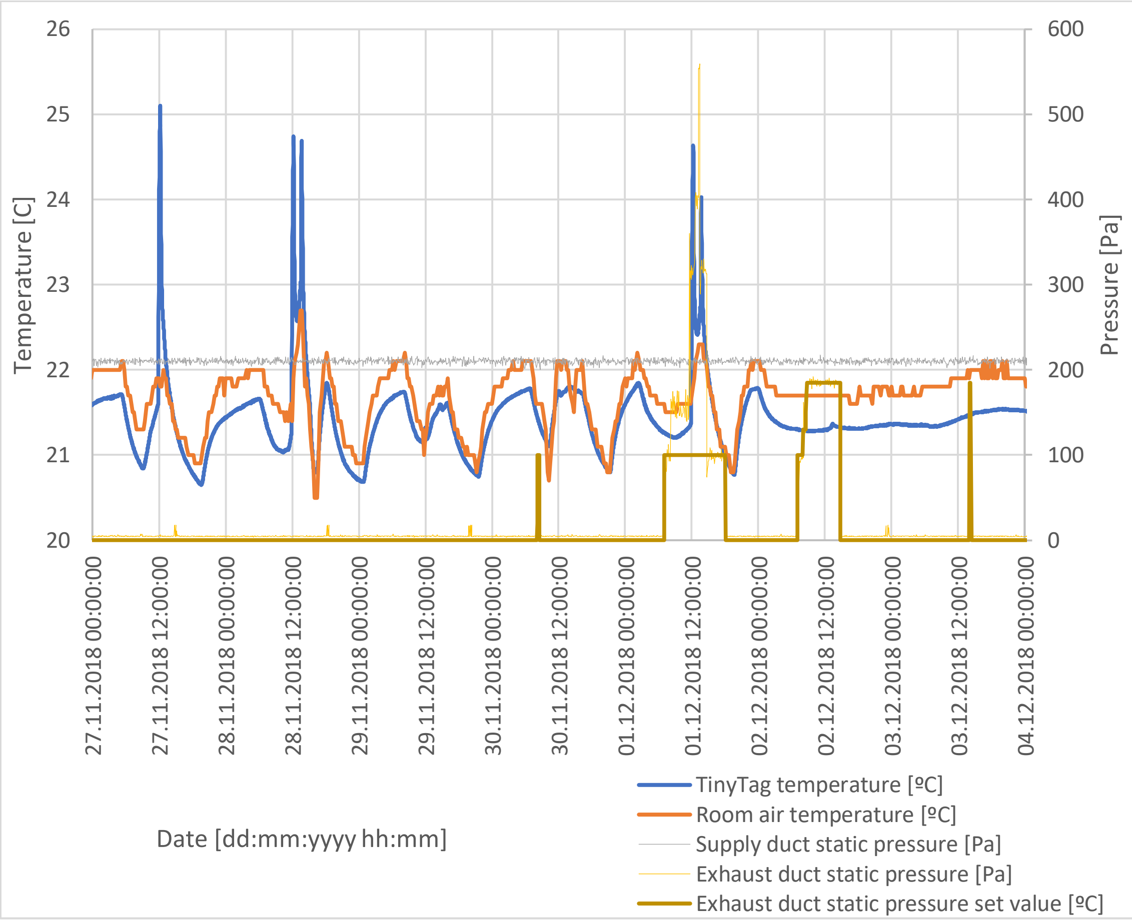


**Figure 29. Room air temperature of separate data logger and building management system data of similar room air temperature and pressure level of ducts.**

Supply duct static pressure remains around 210 Pa throughout the whole monitoring period as designed in a pressure depending DCV system. Measured exhaust duct static pressure remains very low (around 6 Pa) most of the time but still has a few spikes reaching close or over 200 Pa. It is not clear how or if the duct static pressures are supposed to react to the sensors within rooms R304-R313 because the ventilation design drawings considering AHUs were unavailable. Due to the same reason it remains unknown why the exhaust duct static pressure is only 6 Pa and spikes sometimes, but a possible explanation can be a malfunctioning sensor.

### Conclusion

The ventilation system does not work properly in room 307. In normal and boost mode the exhaust airflows are similar to designed values, but the supply airflows are too high. This leads to the high ratio between supply and exhaust airflows that can cause too much excess pressure in the room. The airflows in unoccupied mode were outside measurement range and therefore remains inconclusive.

The room air temperature stays within the designed boundaries. In occupied mode the cooling starts when the room air temperature exceeds 21 ºC and the ventilation boost turns on at 24 ºC. The temperature stays between 20.5 ºC and 22.5 ºC as designed.

There were no automation data on occupancy sensor nor on damper positions and therefore it is impossible to say how the room ventilation reacts to $CO_2$ and temperature sensors during the monitoring measurement period.

The exhaust duct static pressure has a spike in Figure 29 where the duct static pressure is approximately 450 Pa higher than the set value. It remains unknown what causes this, but a 450 Pa difference is an enormous aberration from the duct static pressure set value and thus it is likely that the sensor is malfunctioning.

## 5.3 Otakaari 1

Otakaari 1 (OK1) is a building in Otaniemi campus (Otakaari 1, Espoo) campus owned by ACRE. It used to be the main building for Helsinki University of Technology but now it is officially known as Undergraduate Centre working as a multipurpose building. OK1 is open for everyone and it has work spaces, lecture halls, space for venues, exhibition spaces and a restaurant. The building was designed by Alvar Aalto whom Aalto University is named after. OK1 was completely renovated in 2015 including the ventilation system which was upgraded at that time.

**Figure 30. Otakaari 1 the Aalto Undergraduate Centre.**

From OK1, room U106 was chosen for analysis. Room U106 is a group work space for Aalto University students. The room can be reserved by student with a mobile application which makes it easily accessible. For the analysis, all necessary documents were available considering the ventilation system.

**Ventilation system**

The AHU that ventilates room U106 also serves other group working spaces in the same area and most of the rooms have a VAV-system. Figure 31 shows the ventilation design for room U106. The room has two supply air devices, two exhaust air valves and four dampers. Every supply and exhaust air devices have their own damper to control airflows. The supply air dampers are named U305FZ15.104.01 and U305FZ15.104.02, respectively. Exhaust air damper are named U305FZ17.104.01 and U305FZ17.104.02 in Figure 31. Additionally, the room has two diffusers installed in bulkhead.

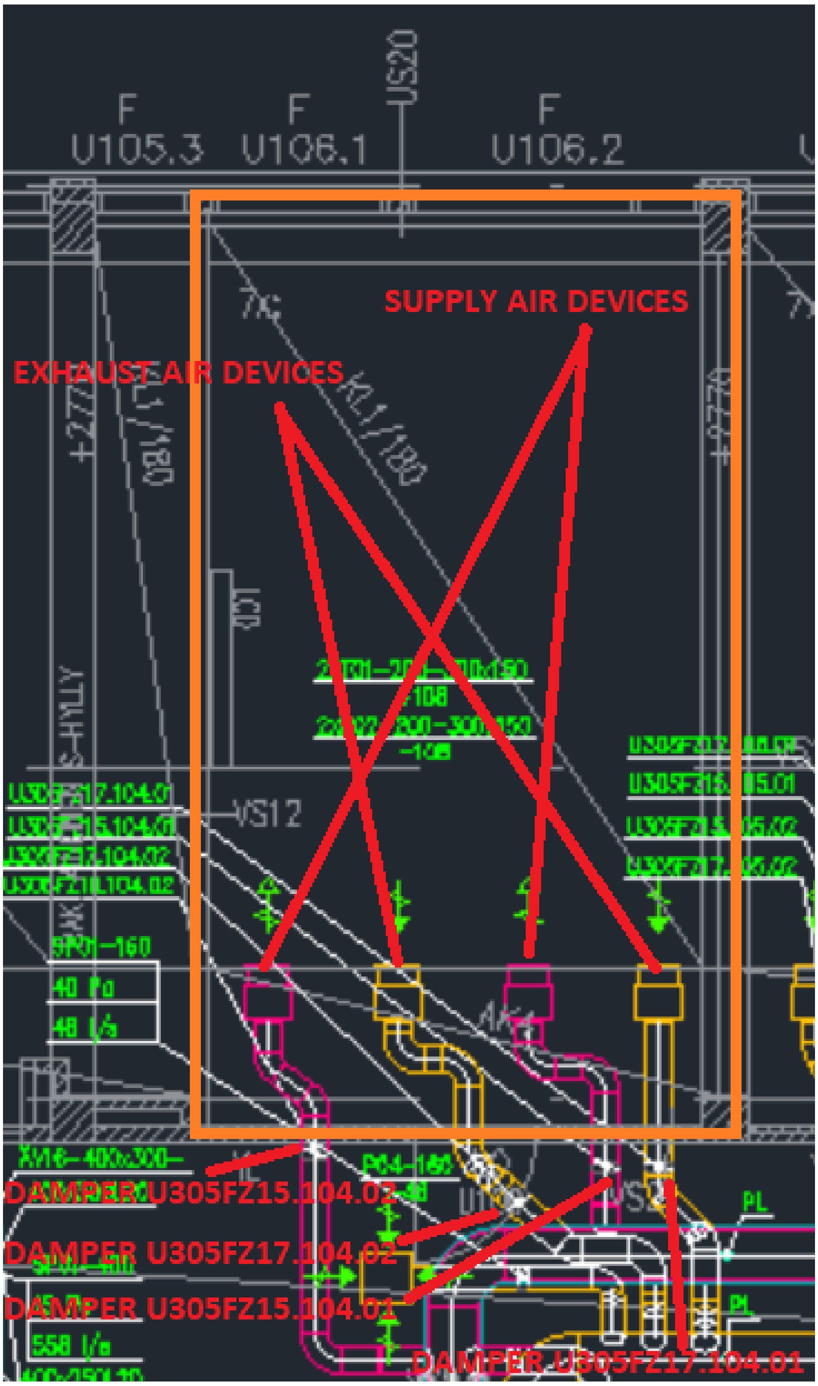


**Figure 31. Ventilation design of room U106 in OK1.**

### Ventilation automation

Room U106 has two operating modes: occupied and unoccupied. Occupancy is monitored with an occupancy sensor. Supply and exhaust dampers are controlled in pairs. Dampers U305FZ15.104.01 and U305FZ17.104.01 are called damper pair 1 and U305FZ15.104.02 and U305FZ17.104.02 are called pair 2. When occupied, the ventilation is in normal mode having damper pair 1 open while pair 2 is closed. In unoccupied mode, both damper pairs should be closed but the room has a flushing function that is constantly on as a default setting keeping damper pair 1 open constantly. Therefore, the room ventilation is on normal mode even when unoccupied.

Boost mode can be activated in three different ways: with the $CO_2$ sensors, temperature sensor or a hand switch. In the boost mode, damper pair 2 is opened.

The occupant can use an occupancy button to boost ventilation for a set period of time (for example 1 h) opening all the dampers.

The $CO_2$ sensor controls ventilation boost on and off depending on $CO_2$ concentration. This is shown in Figure 32. Boost mode is activated when $CO_2$ concentration reaches 750 ppm. The damper pair closes when $CO_2$ concentration decreases under a set level which is not defined in the ventilation design drawings.

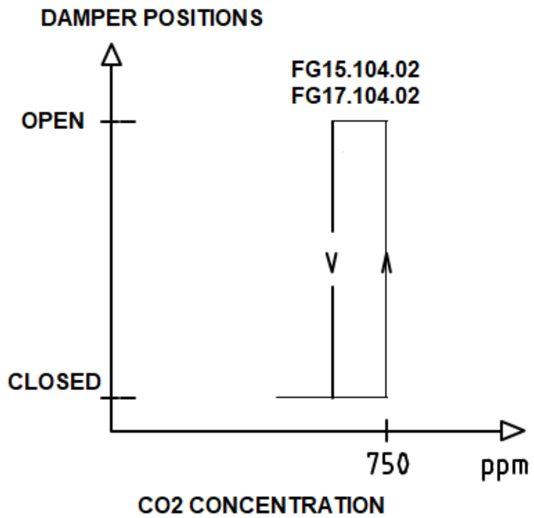


**Figure 32. $CO_2$ sensor U305QE16.104 controlling damper positions for room U106.**

The temperature sensor controls ventilation boost on and off depending on the room air temperature level. This is shown in Figure 33. When occupied, the boost mode is activated when the room air temperature rises above the set temperature level (23 ºC by default). The damper pair is closed when the room air temperature is decreased back to a set level which is not defined in the ventilation design drawings.

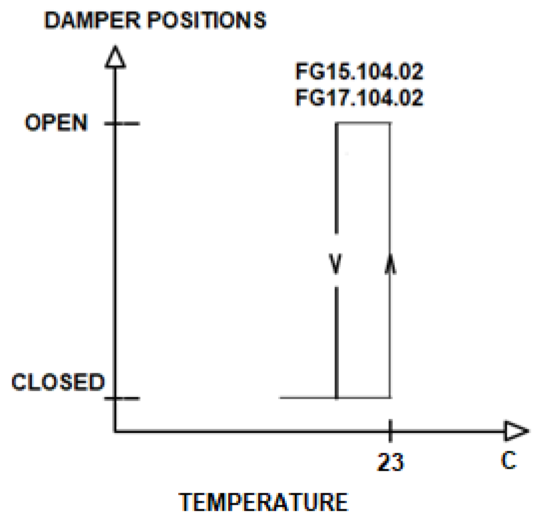


**Figure 33. Temperature sensor U305TE16.104 controlling damper positions.**

The room air temperature is controlled with ventilation and water radiators. The radiators heat the room and the ventilation cools the room depending on which is required. The set room air temperature (default 23 ºC when occupied and 26 ºC when unoccupied) changes depending on outside air temperature. This is shown in Figure 34. When outside air temperature rises, also the room set temperature rises. The set room air temperature can also be controlled with a room panel by ±2 ºC.

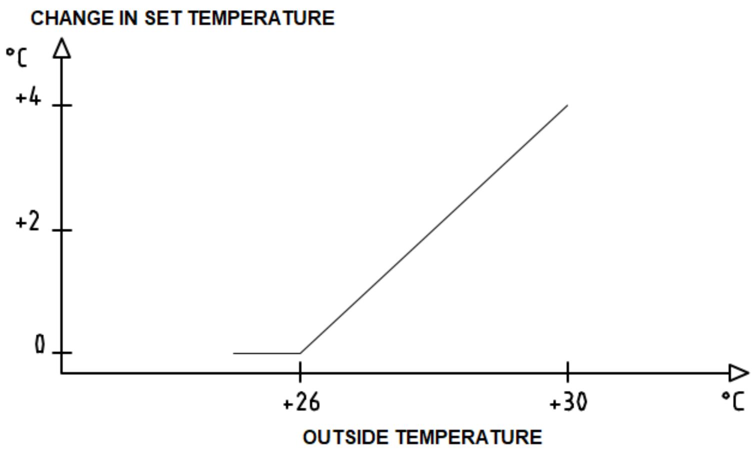


**Figure 34. Room air temperature set point depends on outside air temperature.**

The supply air temperature depends on the outside air temperature. When the outside air temperature is low, the supply air temperature is increased and when the outside air temperature is high, the supply air temperature decreases. This is shown in Figure 35.

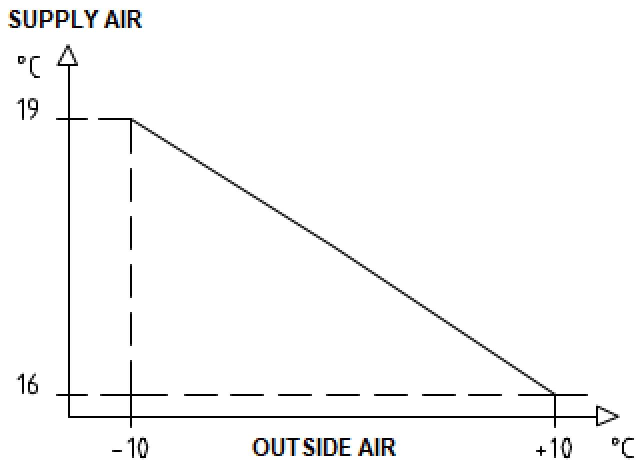


**Figure 35. Supply air temperature depends on outside air temperature.**

### Measured airflow rates

Room U106 has two identical supply air and two exhaust air devices. The measurements were done in normal and boost mode. The results are shown in Table 21.

**Table 21. Measurement results for OK1 room U106.**

| Mode | Supply airflow [l/s] | | Exhaust airflow [l/s] | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|
| | **Measured** | Design | **Measured** | Design | | |
| **Normal** | **58** | 50 | **76** | 50 | **-19** | **75** |
| **Boost** | **105** | 100 | **133** | 100 | **-29** | **78** |

In normal and boost modes, the supply airflows are quite similar to the designed values. The exhaust airflows are not.

The room has higher exhaust airflow compared to the supply airflow which results in under pressure. When the ratio between the airflows is high and it can cause high pressure difference over the envelope and surrounding area.

### Monitoring measurements

Monitoring measurements were done for temperature levels with TinyTag in room U106. The room did not have any suitable place for pressure difference monitoring of supply air devices. Automation data was available for the temperature sensor, the $CO_2$ sensor and damper pair 2 positions. Automation data was not available for the usage of the occupancy button or the control temperature. The measurements and automation data are shown in Figure 36.

From Figure 36, it can be observed that the temperature changes are reasonable between 20-23 ºC inside the room and never exceeding 23 ºC as designed. The TinyTag and the room air temperature sensor measured very similar temperatures during the measurement period.

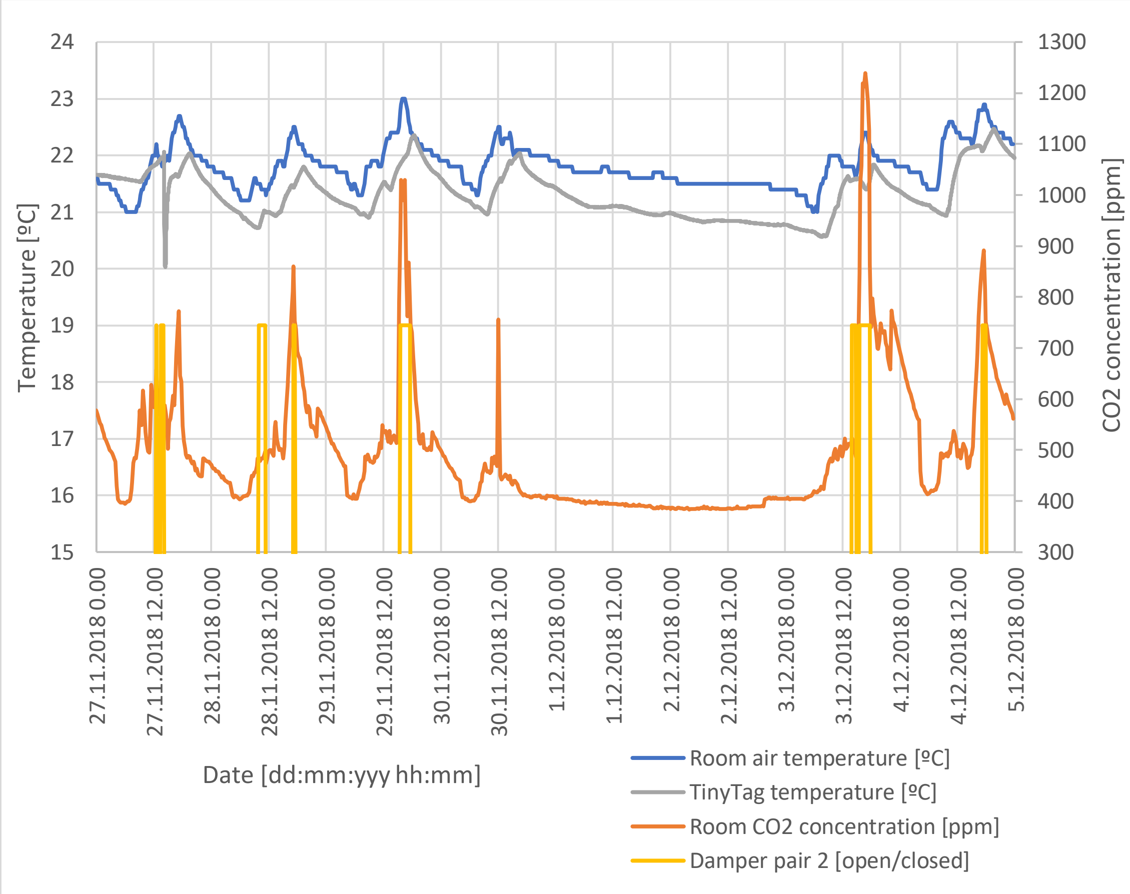


**Figure 36. Temperature monitoring measurement compared to AHU's automation data.**

Figure 36 shows that when $CO_2$ concentration rises above 750 ppm damper pair 2 opens as designed. The dampers have also opened few times when $CO_2$ concentration was below 750 ppm and room air temperature was under 23 ºC indicating that the boost mode has been activated with the room panel.

With this data it is impossible to say how the dampers react to room air temperature since the temperature never exceeded 23 ºC during the measurement period.

## Conclusion

The ventilation does not work properly in room U106. In normal and boost modes, the supply airflows are similar to the designed values, but the exhaust airflows are too high. This leads to high ratio between supply and exhaust airflows that can cause too much under pressure in the room.

The room air temperature stays within the designed values. The room air temperature stays between reasonable levels 20-23 ºC never exceeding the minimum room set temperature 23 ºC.

The dampers react properly to $CO_2$ concentration. Every time the $CO_2$ concentration exceeds 750 ppm, the boosting dampers open as designed. Also, damper automation data indicates that the room occupants have used the ventilation boost button to boost ventilation.

All the necessary ventilation drawings about the control strategy of ventilation were available.

## 5.4 Open Innovation House

Open Innovation House (OIH) is a building in Otaniemi campus (Maarintie 6, Espoo) owned by ACRE. It has spaces of Pohjois-Tapiola high school, restaurant and offices.

**Figure 37. Open Innovation house (OIH).**

From OIH room B205 was chosen for analysis. It is a meeting room for staff. The ventilation drawings only included the AutoCAD drawings of the ventilation system excluding all drawings considering the control strategy of the ventilation system. The documents did not include the types of the terminal units either.

### Ventilation system

The AHU that ventilates room B205 also serves other similar meeting rooms but only room B205 has VAV-terminal units. Figure 38 shows the ventilation design for room B205. The room has two chilled beams (Swegon Pacific) for supply air, two exhaust air valves and three dampers. The chilled beams are connected to cooling valves that are not shown in Figure 38. Dampers 307IMS15.2.9.1 and 307IMS15.2.9.2 control the airflow for both supply air devices. Damper 307IMS17.2.9 controls the airflow for both exhaust air devices.

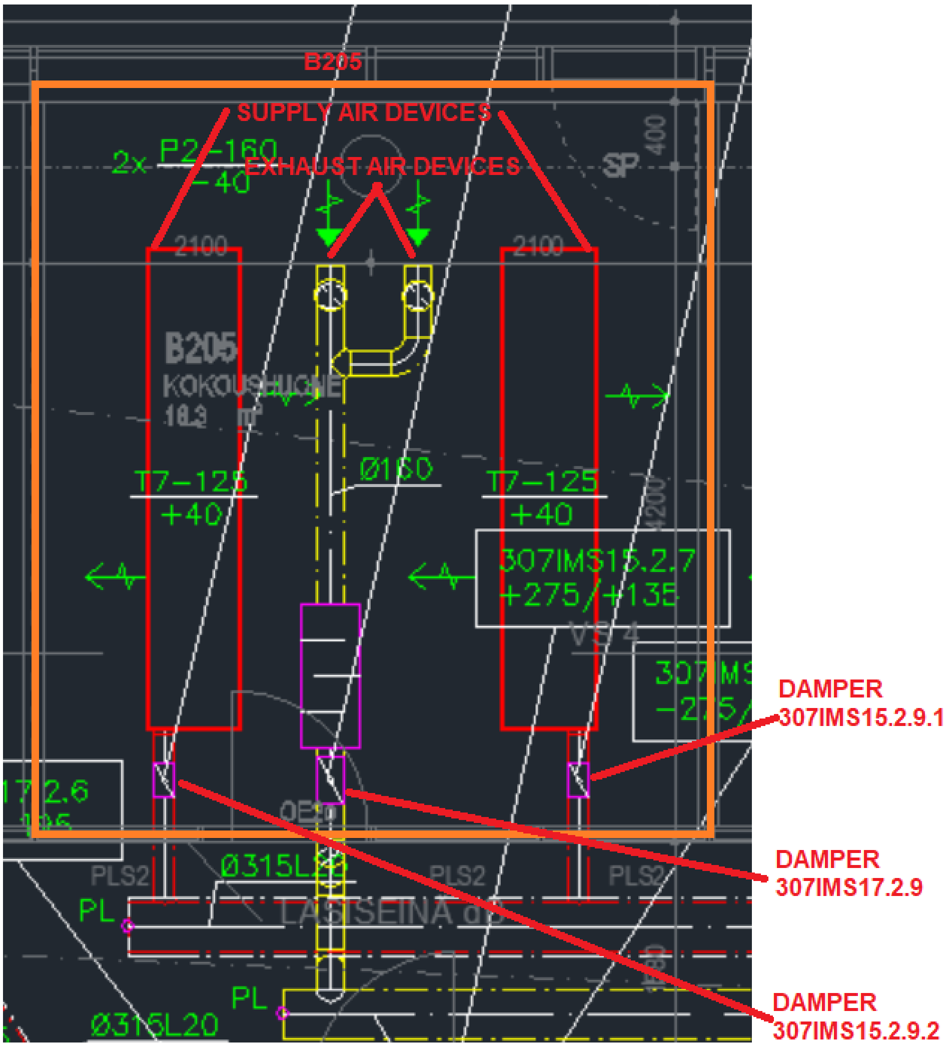


**Figure 38. Ventilation design for room B205.**

### Ventilation automation

The ventilation in room B205 is controlled by $CO_2$ and temperature sensors. In the boost mode, the IMS dampers open fully and otherwise the dampers are in “minimum” mode. The minimum mode is not specifically defined in the automation design drawings.

The $CO_2$ sensor controls the IMS dampers. At 500 ppm or below, the IMS dampers are at minimum mode and after reaching 500 ppm the IMS dampers start to open relatively until $CO_2$ concentration is above 700 ppm when the IMS dampers fully open. This is shown in Figure 39.

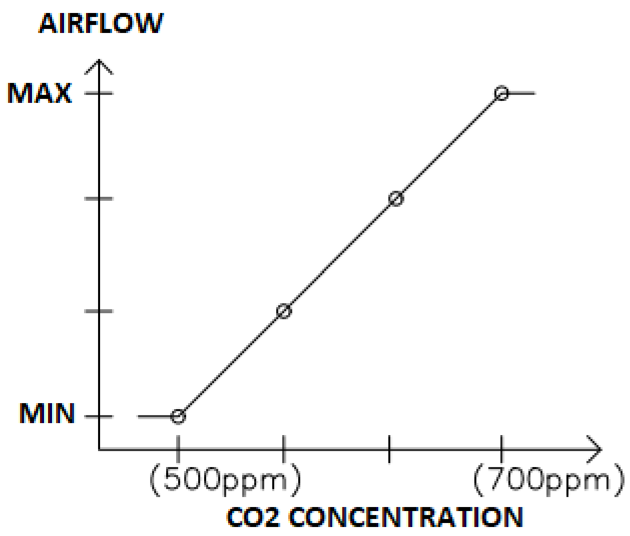


**Figure 39. $CO_2$ sensor controlling airflows for room B205.**

The room air temperature is controlled with ventilation and water radiators. The radiators heat the room and ventilations provides cooling depending on what is required. The room has a temperature sensor that controls the IMS dampers. When the room air temperature is 23 ºC or below the IMS dampers are at minimum mode. The IMS dampers start to open relatively after reaching 23 ºC and until the room air temperature is 24 ºC after which the IMS dampers are fully opened. This is shown in Figure 41.

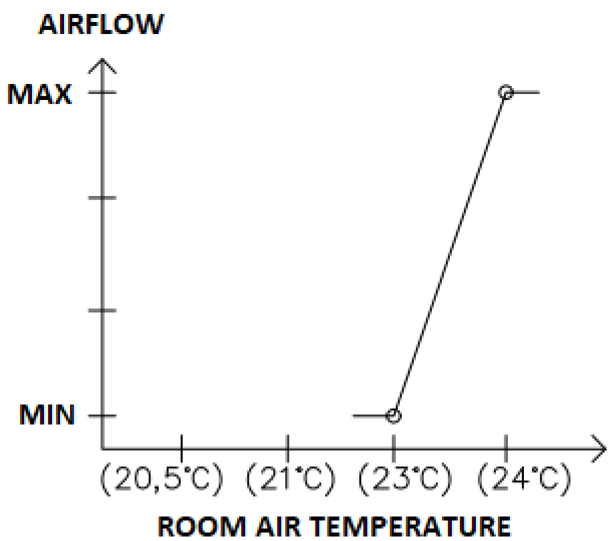


**Figure 40. The temperature sensor controlling airflows for room B205.**

The supply air temperature depends on the exhaust air temperature. When the exhaust air temperature is 20 ºC or less, the supply air temperature is 22 ºC. When the exhaust air temperature is 25 ºC or above, the supply air temperature is 15 ºC. The supply air temperature changes linearly between 15-22 ºC compared to the exhaust air temperature. This is shown in Figure 41.

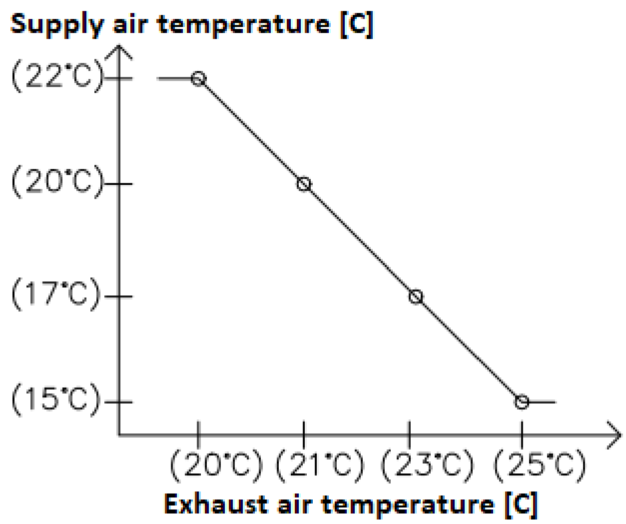


**Figure 41. Supply air temperature depends on the exhaust air temperature.**

### Measured airflow rates

Room B205 has 2 identical supply air and 2 exhaust air devices. The measurements were done in normal and boost modes and the results are shown in Table 22.

**Table 22. Measured airflow rates for Open Innovation House room B205.**

| Mode | Supply airflow [l/s] | | Exhaust airflow [l/s] | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|
| | Measured | Design | Measured | Design | | |
| **Normal** | **38** | N/A | **49** | N/A | **-11** | **78** |
| **Boost** | **44** | 80 | **53** | 80 | **-9** | **83** |

The designed values for normal mode were not available and therefore it remains unknown whether the measured airflow rates in normal mode are similar to the designed values. The pressure difference to the surrounding areas was measured. In normal mode the ratio between supply and exhaust airflows is causing under pressure over the hallway of 15.5 Pa.

In boost mode the airflows are much lower than the designed values. The airflow differences between normal and boost mode are small. The ratio between supply and exhaust in boost mode is slightly better compared to normal mode.

### Monitoring measurements

Monitoring measurements for room air temperature were done with TinyTag and for pressure differences with Sensirion for room B205, but no automation data was available. Pressure differences were measured for both supply air devices with pressure sensors A and B. The measurement results are shown in Figure 42.

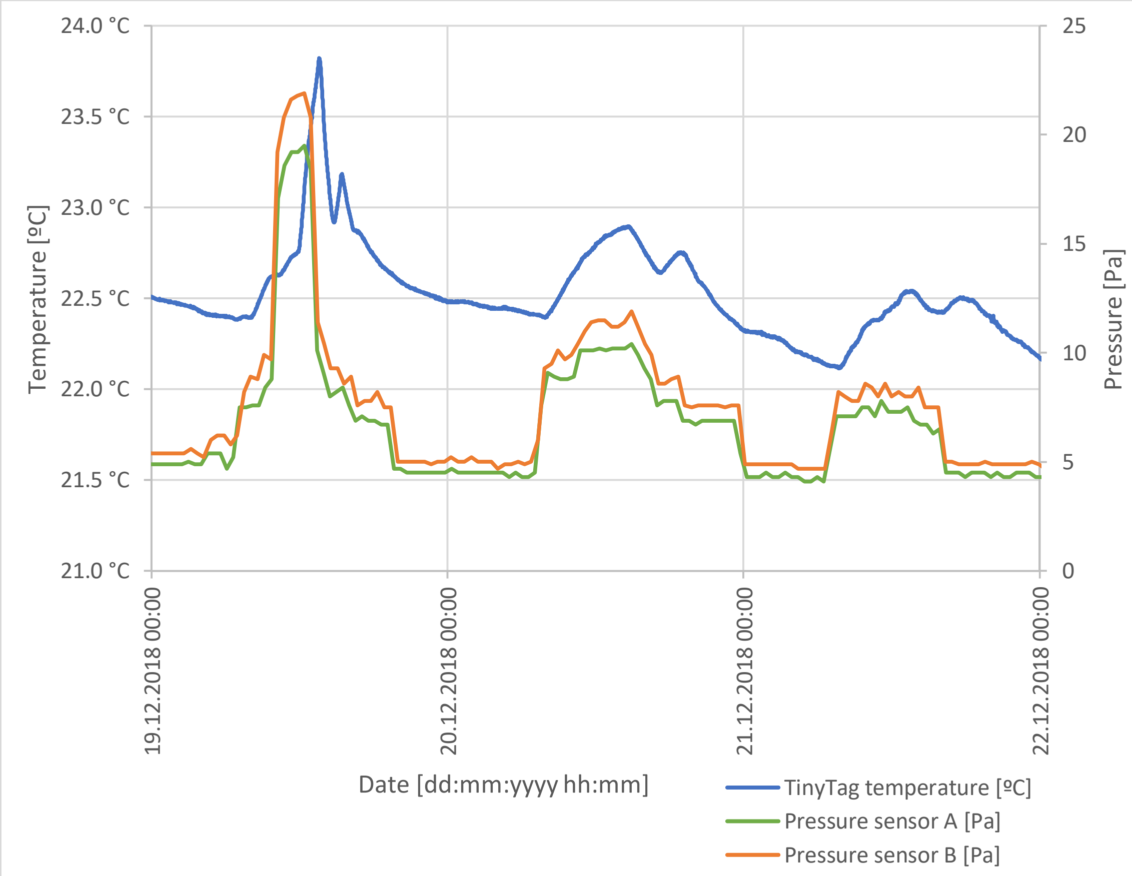


**Figure 42. Temperature monitoring measurement compared to pressure difference monitoring measurement.**

The room air temperature stays in between acceptable levels. The room air temperature stays between 22-24 ºC staying mostly closer to 22.5 ºC never reaching above 24 ºC when full boost mode is activated. The duct static pressures increase every time the temperature is getting close to 22.5 ºC showing that the IMS dampers react to room air temperature.

## Conclusion

The ventilation does not work properly in room B205. In normal mode the ventilation causes a 15.5 Pa under pressure over the hallway due to the high ratio between supply and exhaust airflows. In the boost mode, the airflows are far too low compared to the designed values also causing the same under pressure to the hallway. The difference between normal mode and boost mode airflows are insignificant.

The room air temperature stays within acceptable levels of 22-24 ºC being mostly closer to 22.5 ºC. The exact set room air temperature cannot be defined but around at 23 ºC the ventilation boost is activated. It is likely that the cooling valves in the chilling beam try to cool the room first and the ventilation is boosted if the room temperature keeps increasing. This can also work the other way around so that the ventilation cools the room primarily and the chilling beam's cooling valves open if the set temperature cannot be reached by ventilation alone.

There were no automation data available from room B205. Hence, it remains unknown how the ventilation system reacts to $CO_2$ concentration.

## 5.5 Learning Centre

Learning Centre is a building in Otaniemi campus (Otaniementie 9, Espoo) owned by ACRE. The building was originally designed by Alvar Aalto to be a library. The building was renovated in 2015 (including the ventilation system) and it has since then been called Harald Herlin Learning Centre. The Learning Centre has a library, work spaces, offices, exhibition spaces, cafeteria and group working spaces.

**Figure 43. Learning Centre.**

From Learning Centre, the room 136 was chosen for analysis. The room is an office for employees of Aalto University. All required documents were available in the control strategy of ventilation system.

### Ventilation system

The AHU that ventilates room 136 also serves other similar rooms. Figure 44 shows the ventilation design for room 136. The room has two square shaped chilled beams (Halton CBX) for supply air, two exhaust air devices and four dampers. The chilled beams are connected to cooling valves that are not shown in Figure 44. Damper FZ15.136 controls one supply air device's airflow and damper FZ17.136 controls one exhaust air device's airflow and together the dampers are called damper pair FZ. The other two dampers are not controlled by the ventilation automation and remain open at all times for one exhaust and one supply air device.

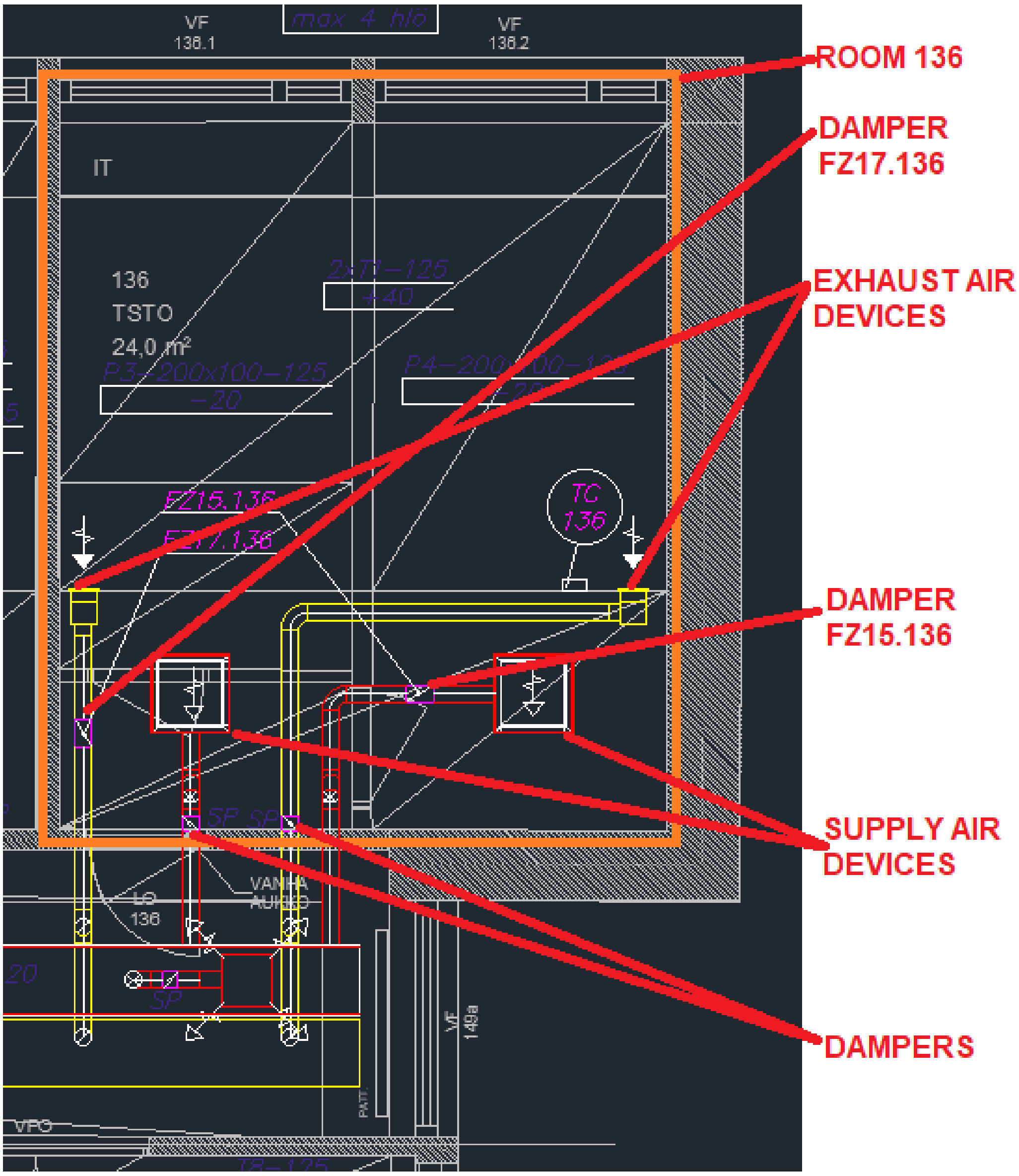


**Figure 44. Ventilation design for room 136.**

### Ventilation automation

Room 136 has two operating modes: occupied and unoccupied. The ventilation automation system controls the operating mode with a timed schedule. In occupied and unoccupied modes (normal mode) damper pair FZ is closed. It remains unclear from the ventilation automation drawings how the ventilation works in unoccupied mode. It is likely that when the rooms are in unoccupied mode the airflows are reduced or turned off. The room also has an occupancy button that can be used. If the occupancy button is used in unoccupied mode, the room is changed to occupied mode and the AHU starts to ventilate the room in normal mode for a designated time window. If the occupancy button is pressed in occupied mode, the boost mode is activated.

The room has three alternatives to activate boost mode: occupancy button, $CO_2$ sensor and room air temperature. In the boost mode, damper pair FZ is opened.

Room specific $CO_2$ sensor controls ventilation boost on and off depending on $CO_2$ concentration. This is shown in Figure 45. Boost mode is activated when $CO_2$ concentration reaches 800 ppm and turning back on normal mode when $CO_2$ is under 800 ppm.

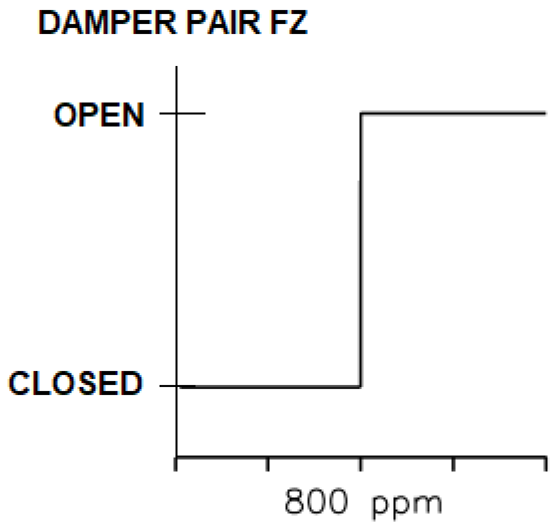


**Figure 45. $CO_2$ sensor controlling damper positions for room 136.**

The room air temperature is controlled with ventilation and water radiators. The radiators heat the room and the ventilation cools the room depending on which is required. Room specific temperature sensor controls ventilation boost on and off depending on room air temperature. This is shown in Figure 46. Boost mode is activated when the room air temperature reaches 25 ºC and turns back on normal mode the temperature is under 25 ºC. Before reaching 25 ºC, the room is first being cooled with the chilled beams and after when the cooling valves are fully opened at 25 ºC the boost mode is activated.

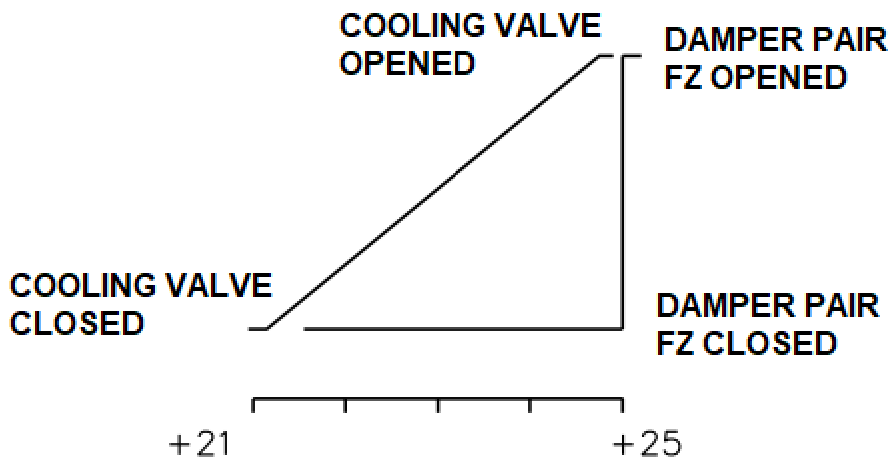


**Figure 46. Temperature sensor controlling cooling valves and damper positions for room 136.**

There are two options how the supply air temperature can be controlled, and it remains unknown which one is being used due to the lack of automation data. In both options the supply air temperature is between 16-22 ºC. In the option one, the supply air temperature is controlled so that the exhaust air temperature stays within a set value by changing the temperature of supply air. In the option two, the supply air temperature depends on the outside air temperature.

### Measured airflow rates

Room 136 has two identical supply air and exhaust air devices. The measurements were done in the normal and boost modes. The results are shown in Table 23.

**Table 23. Measured airflow rates in Learning Centre room 136.**

| Mode | Supply airflow [l/s] | | Exhaust airflow [l/s] | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|
| | Measured | Design | Measured | Design | | |
| **Normal** | **20** | 20 | **22** | 20 | **-3** | **88** |
| **Boost** | **38** | 40 | **45** | 40 | **-7** | **85** |

In the normal and boost modes, the airflows are similar to the designed airflows. Ratios between supply and exhaust airflows can cause under pressure over the envelope and surrounding area.

### Monitoring measurements

Monitoring measurements for room air temperature were done with TinyTag. The room did not have any suitable place for pressure difference monitoring of supply air devices and no automation data was available for room 136. The measurement results are shown in Figure 47.

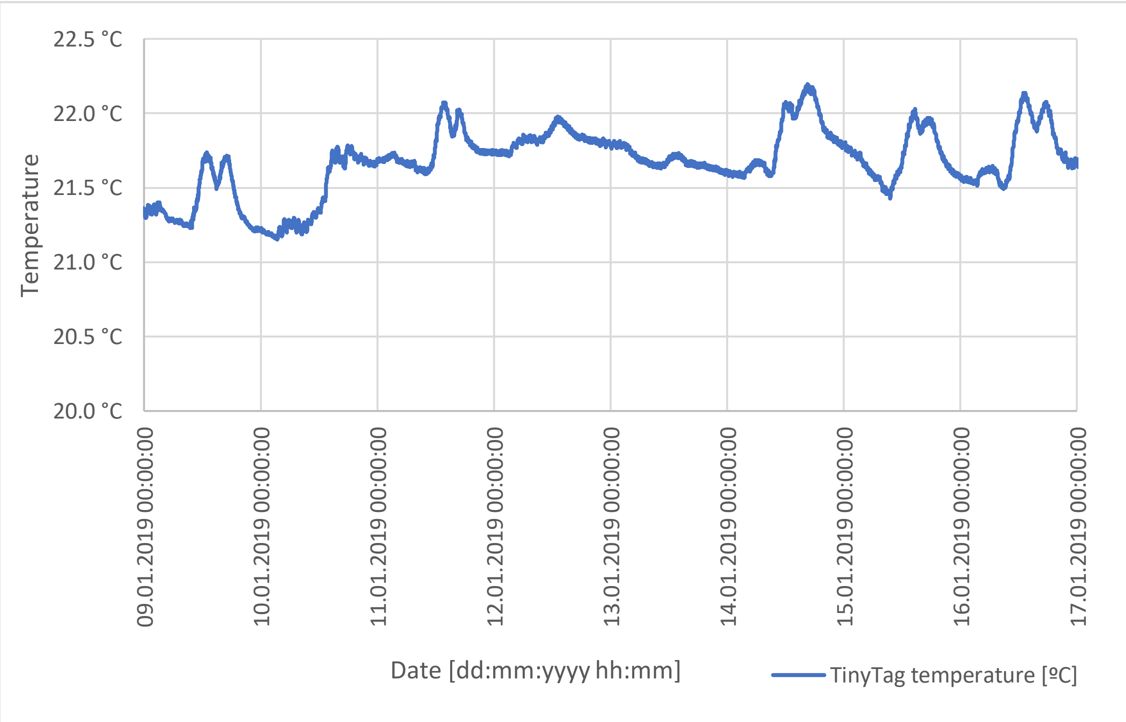


**Figure 47. Room air temperature measurements.**

The room air temperature stays within the designed boundaries. The room air temperature constantly remains between 21-22.5 ºC not even coming close to 25 ºC which would activate the boost mode. The cooling valves start to cool the room already at 21 Cº.

### Conclusion

Ventilation works properly in normal and boost mode. The airflows in normal and boost mode are very similar to the designed values, and the ratio between supply and exhaust airflows remain in acceptable levels not causing too much under pressure over the envelope and surrounding area.

The room air temperature stays within the designed boundaries. The room air temperature stays between 21-22.5 ºC not coming close to 25 ºC when boost mode would be activated. If the room air temperature sensor measures a temperature constantly above 21 ºC like TinyTag it is possible that the radiators heat the room and at the same time ventilation is trying to cool the room. Cooling valves start to open gradually at 21-25 ºC.

Automation data was not available for room 136. Therefore, it remains unknown how the ventilation system reacts to $CO_2$ concentration, temperature and occupancy button while in normal use.

All the necessary ventilation drawings about the control strategy of ventilation were available.

## 5.6 TUAS

TUAS is a building in Otaniemi campus (Maarintie 8, Espoo) owned by ACRE. It was built in 2003 and now operates as the main building for Aalto School of Science and Aalto School of electrical engineering. TUAS is open for everyone and it has work spaces, lecture halls, space for venues, and a restaurant.

**Figure 48. TUAS building.**

From TUAS room 2104 was chosen for analysis. The room is a meeting room for employees of Aalto University. All required documents were available of the control strategy of ventilation system.

### Ventilation system

The AHU that ventilates room 2104 also serves other similar rooms. Figure 49 shows the ventilation design for room 2104. The room has one chilled beam for supply air, two supply air diffusers, three exhaust air valves and two dampers. The chilled beam is connected to cooling valves that are not shown in Figure 49. Damper pair TU controls room airflows where TU215.02 controls airflows for all supply air devise and damper TU317.02 controls airflows for all exhaust air devices.

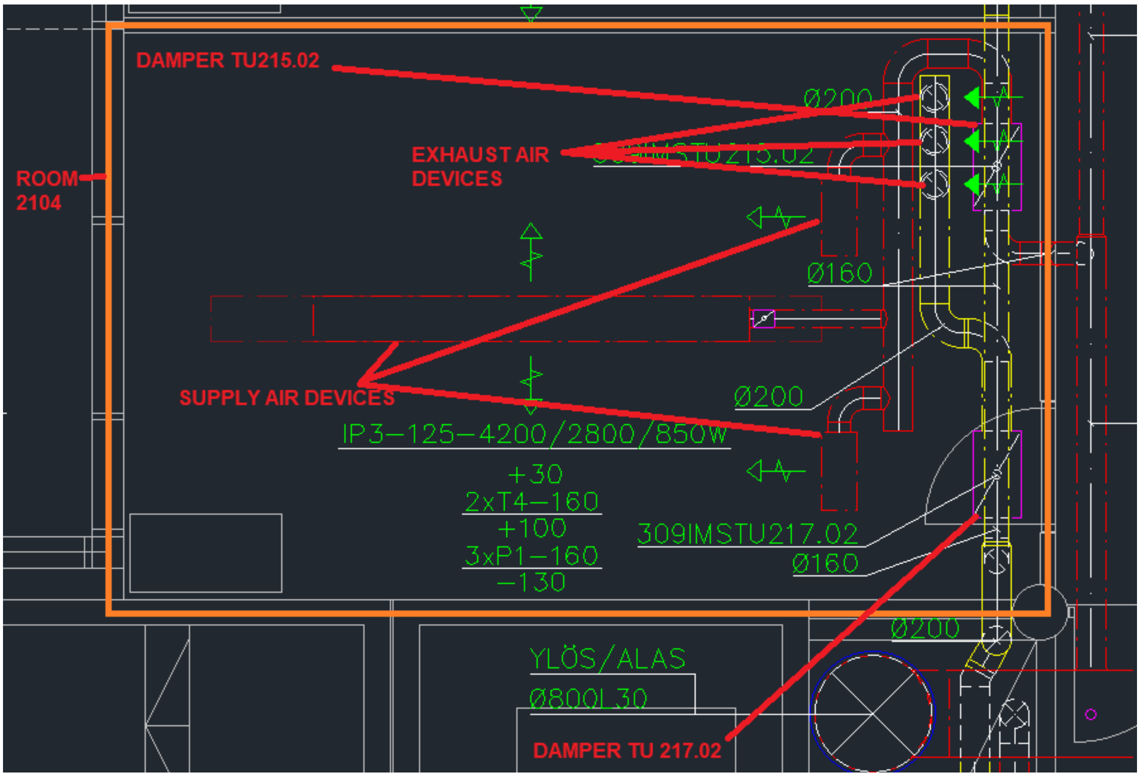


**Figure 49. Ventilation design for room 2104.**

### Ventilation automation

Room 2104 has two operating modes: occupied and unoccupied. Occupancy is defined with an occupancy sensor and with an occupancy time schedule. Ventilation is turned off outside occupancy time schedule but is turned on if any occupancy sensor connected to AHU 307 is triggered. After, the ventilation is shut down when no occupancy is detected with any sensor.

The room has 2 sensors that activate the boost mode: $CO_2$ and room air temperature sensors. In the boost mode, damper pair TU is fully opened.

The $CO_2$ sensor controls damper pair TU. When the $CO_2$ concentration reaches above a set limit the dampers open relatively to the $CO_2$ concentration. This is shown in Figure 50.

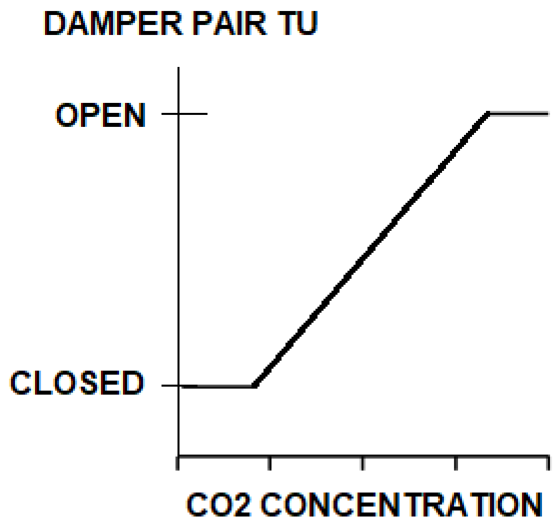

**Figure 50. $CO_2$ sensor controlling damper positions for room 2104.**

The room air temperature is controlled with ventilation and water radiators. The radiators heat the room and the ventilation cools the room depending on which is required. The temperature sensor controls damper pair TU depending on room air temperature. Damper pair TU keeps the room air temperature on set value (default 21 ºC) boosting ventilation if the set value is exceeded. If damper pair TU is fully opened and the set temperature cannot be reached, the cooling valves for the chilling beam open.

The supply air temperature depends on the outside air temperature. When the outside air temperature is low, the supply air temperature is increased and when the outside air temperature is high, the supply air temperature decreases. This is shown in Figure 51.

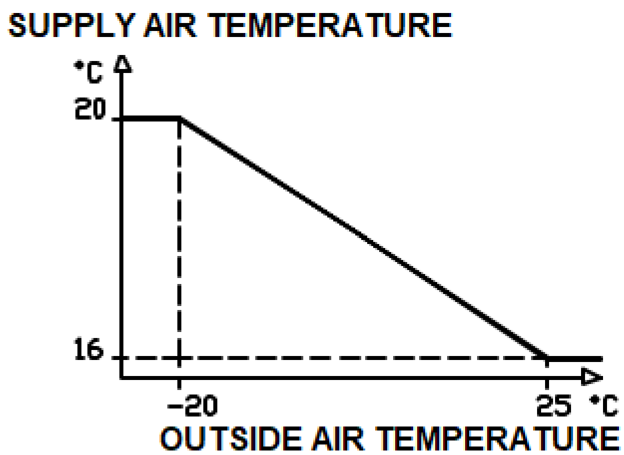

**Figure 51. Supply air temperature depends on outside air temperature.**

### Measured airflow rates

In room 2104, two supply diffusers are the same type and there is also one chilled beam installed in the room. All three exhaust air devices are same models. The measurements were done only in boost mode since the ventilation was constantly on boost mode. The measurement results are shown in Table 24.

Table 24. Measurement results for TUAS room 2104.

| Mode | Supply airflow [l/s] | | Exhaust airflow [l/s] | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|
| | Measured | Design | Measured | Design | | |
| Boost | 78 | 100 | 106 | 100 | -28 | 73 |

In the boost mode, the exhaust airflow is similar to the designed value and the supply airflow is not. The high ratio between supply and exhaust airflows can cause too much under pressure over the envelope and surrounding areas.

### Monitoring measurements

Monitoring measurements for room air temperature were done with TinyTag. The room did not have any suitable place for pressure difference monitoring of supply air devices and no automation data was available for room 2104. The measurement results are shown in Figure 52.

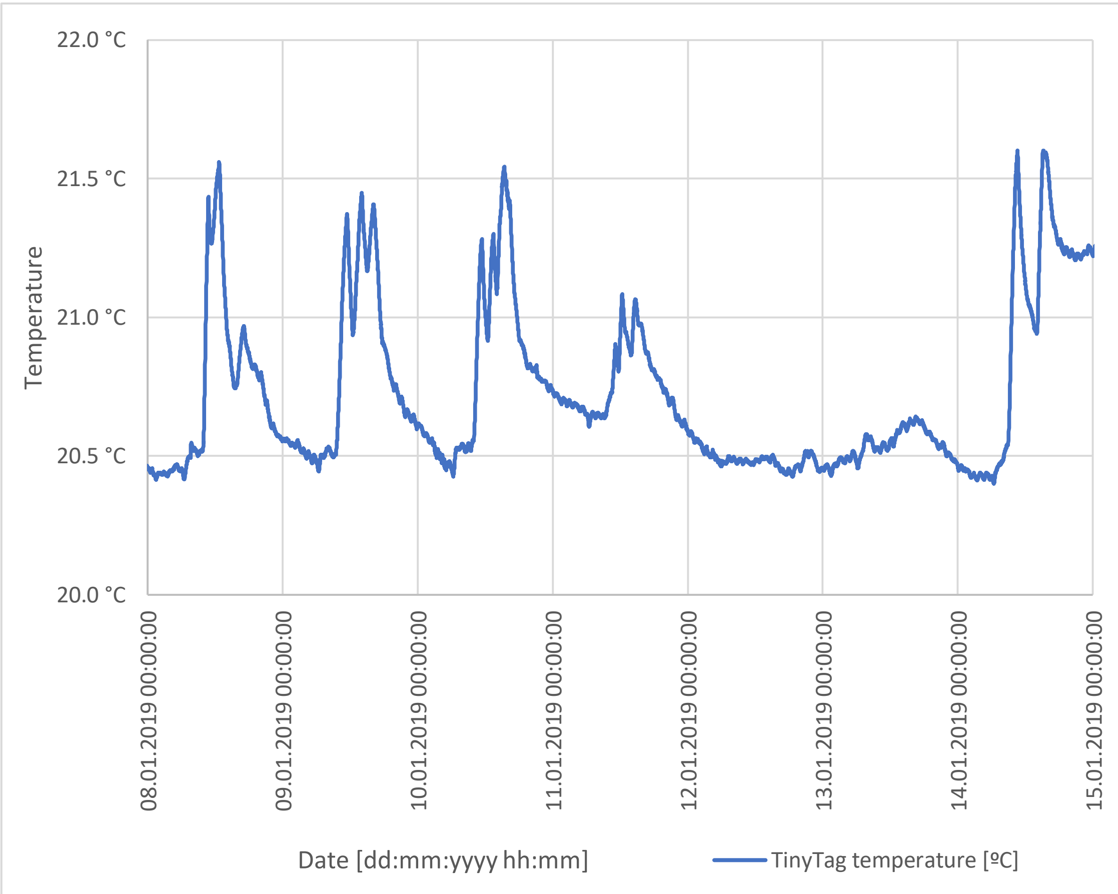


Figure 52. Room air temperature measurements.

The room air temperature stays within the designed boundaries. The room air temperature stays between 20-22 ºC and not staying long periods of time above 21 ºC which is the set room air temperature.

### Conclusion

Ventilation does not work in the boost mode. The airflows are designed to be 6 l/s/person for 30 person the supply airflow lower than the designed value and the ratio between supply and exhaust airflows is too high.

The ventilation system might have a problem with adjusting between normal and boost mode. The temperature is mostly under 21 ºC and therefore should not be keeping the boost mode on. It is possible that the set values for $CO_2$ concentration have been set too low keeping the boost mode on constantly. The boost mode was active already when the room was visited first time in the morning when $CO_2$ concentration should be very low.

Automation data was not available for the room 2104 but all the necessary ventilation drawings about the control strategy of ventilation were available.

## 5.7 School in Helsinki

The school in Helsinki is owned by City of Helsinki. It is an upper secondary school that is specialized in visual arts. The building was renovated in 2016 including the ventilation system. The building consists mainly of classrooms, but it also has a gymnasium and a restaurant.

From the school in Helsinki, room 221 was chosen for analysis. The room is a psychology and religion classroom for students. All required documents were available considering the control strategy of ventilation system.

### Ventilation system

The AHU that ventilates room 221 also serves several other classrooms as well. Figure 53 shows the ventilation design for room 221. The room has two nozzle ducts for supply air, three exhaust air valves and two dampers. All the supply airflow is controlled by damper 203IMS05.221 and all of the exhaust airflow is controlled by damper 203IMS10.221. Together the dampers are named damper pair IMS

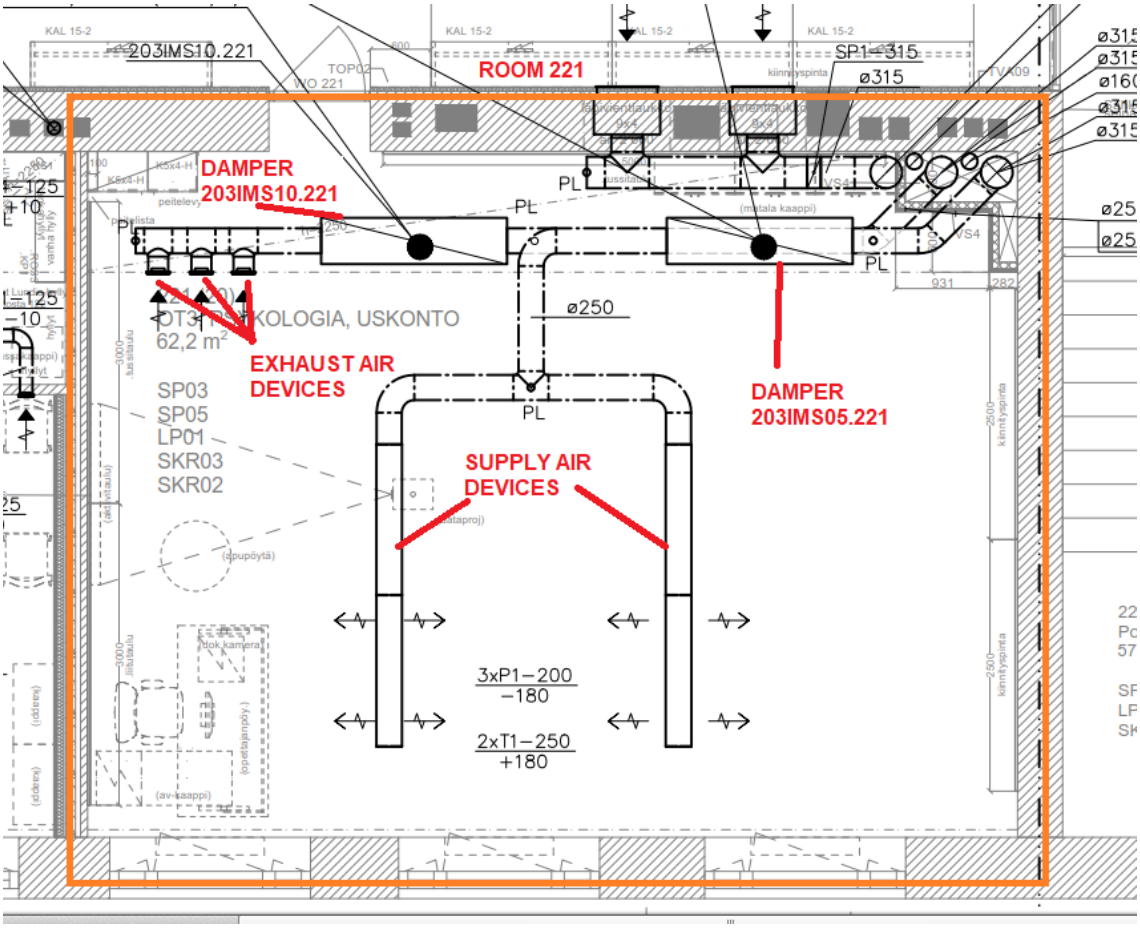


Figure 53. Ventilation design of room 221.

### Ventilation automation

Room 221 ventilation is controlled by $CO_2$ and temperature sensors. In the boost mode, damper pair IMS is fully opened. In the normal mode, the dampers are opened to the minimum position, which is not specifically described in the design drawings.

The $CO_2$ sensor controls damper pair IMS. When $CO_2$ concentration reaches above 700 ppm, the dampers start to open relatively to $CO_2$ concentration. This is shown in Figure 54. The dampers are fully opened when $CO_2$ concentration reaches 900 ppm.

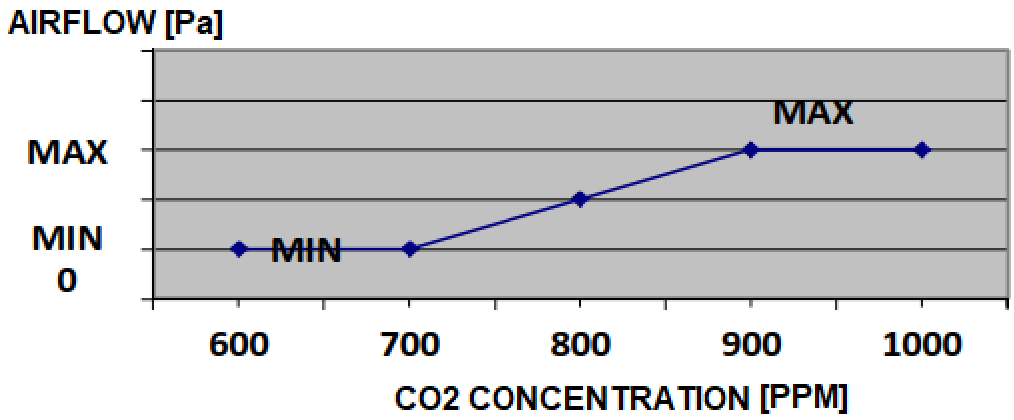


**Figure 54. $CO_2$ sensor controlling damper positions for the room 221.**

The room air temperature is controlled with ventilation and water radiators. The radiators heat the room and the ventilation cools the room depending on which is required. Also, the temperature sensor controls damper pair IMS depending on room air temperature. Damper pair IMS keeps the room air temperature under the set point increasing ventilation relatively when room air temperature exceeds 24 ºC. This is shown in Figure 55. Damper pair IMS is fully opened when room air temperature exceeds 26 ºC.

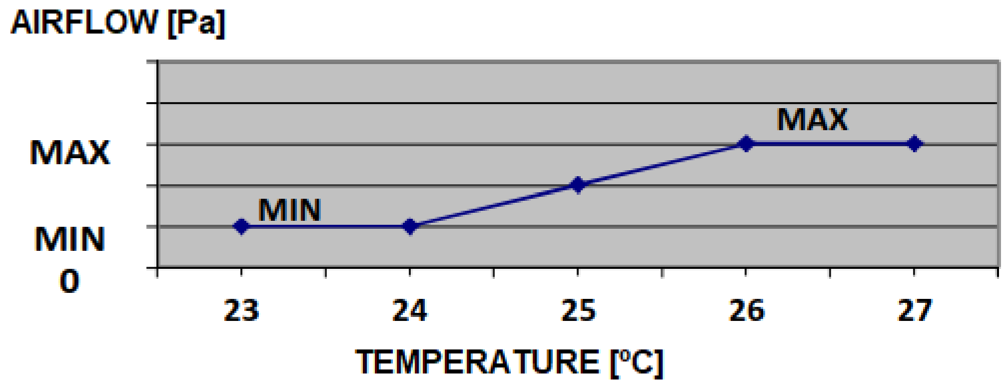


**Figure 55. Temperature sensor controlling damper positions for room 221.**

The supply air temperature depends on the outside air temperature. When the outside air temperature is low, the supply air temperature is increased and when the outside air temperature is high, the supply air temperature decreases. This is shown in Figure 51.

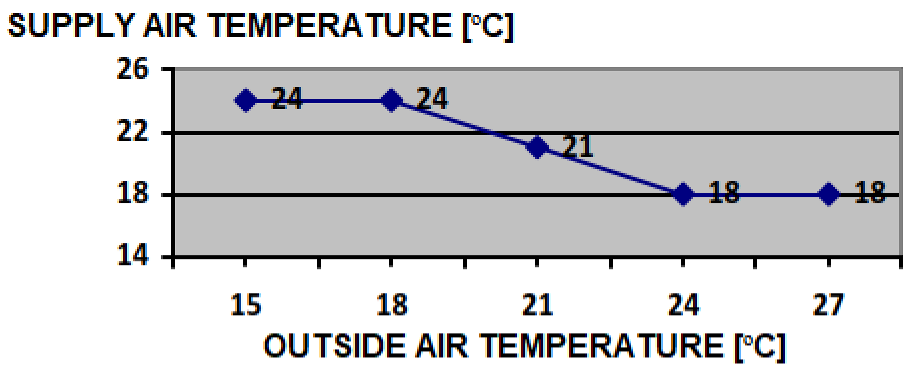


**Figure 56. Supply air temperature depends on outside air temperature.**

### Measured airflow rates

Room 221 has two nozzle ducts for supply air and three exhaust air devices. The measurements were done in the normal and boost modes (100 %). The results are shown in Table 25.

**Table 25. Measurement results for the school in Helsinki room 221.**

| Mode | Supply airflow | | | Exhaust airflow | | | Difference [l/s] | Ratio [%] |
|---|---|---|---|---|---|---|---|---|
| | Measured [l/s, l/s m2] | | Design [l/s] | Measured [l/s, l/s m2] | | Design [l/s] | | |
| **Normal** | **56** | **0.9** | N/A | **36** | **0.6** | N/A | **20** | **157** |
| **Boost** | **143** | **2.3** | 180 | **81** | **1.3** | 180 | **61** | **176** |

The designed values are not defined for normal mode since damper position "minimum" is not defined. In the boost mode, the airflow rates are too low from the designed values and do not meet with the minimum airflow requirements of Sisäilmayhdistys ry for teaching spaces of 3 l/s/m$^2$ or 6 l/s/person. Also in the normal and boost modes, the ratios between supply and exhaust airflows are too high and cause excessive pressure over the envelope and surrounding areas. The measured pressure difference is only 4 Pa outdoors and 0.5 Pa at the hallway.

### Monitoring measurements

Monitoring measurements for room air temperature were done with TinyTag. The room did not have any suitable place for pressure difference monitoring of supply air devices and no automation data was available for room 221. The measurement results are shown in Figure 57.

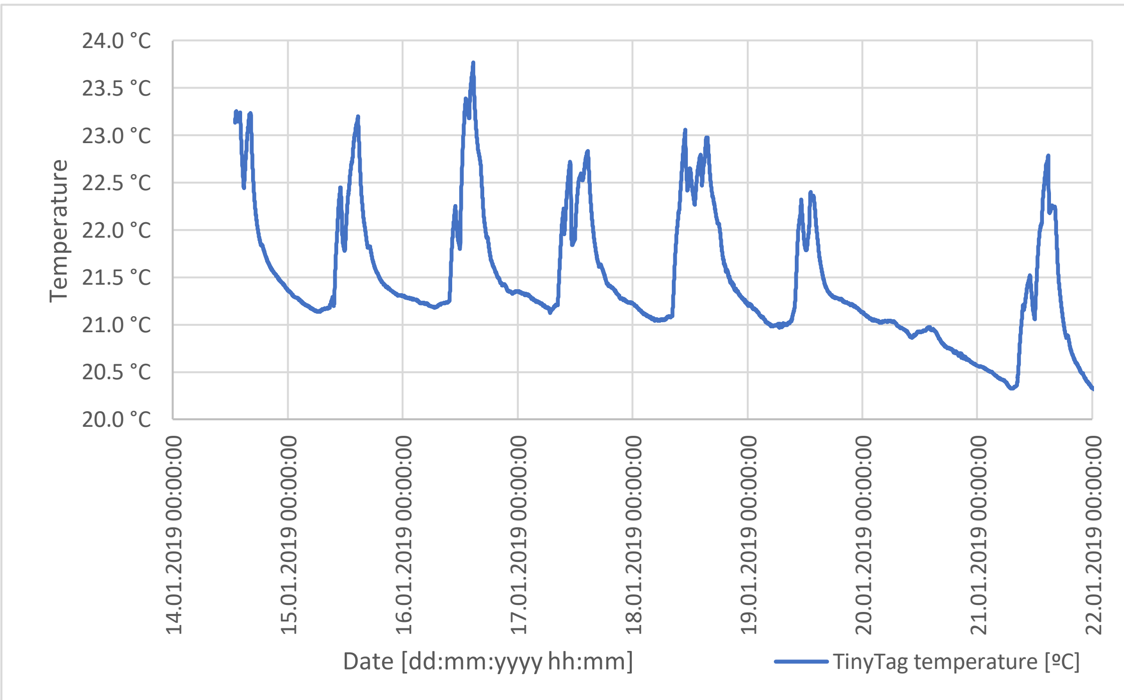


**Figure 57. Room air temperature measurements.**

The room air temperature stays within the designed boundaries. The room air temperature stays between 20-24 ºC not exceeding the room set temperature of 24 ºC.

#### Conclusion

Ventilation does not work properly in the normal nor boost modes. The classroom is designed for 30 people and the supply airflows are designed according to Sisäilmayhdistys ry's classification standards into class S3, 6 l/s/person or 3 $l/s/m^2$, resulting in overall design airflow of 180 l/s. In the full boost mode, these requirements are not met. The exhaust and supply airflows are too low from the designed values and also the ratios between the airflows are too big. Based on the carried out measurements, this does not cause too high excessive pressure over the envelope and surrounding areas which remain at only 4 Pa outdoors and 0.5 Pa at the hallway.

The room air temperature stays within the designed boundaries. The room air temperature stays between 20-24 ºC not exceeding the room set temperature 24 ºC.

Automation data was not available for room 221 but all the necessary ventilation drawings about the control strategy of ventilation were available.

## 5.8 Vocational school

The vocational school in Helsinki is owned by the City of Helsinki. The building was renovated in 2012 including the ventilation system. The building mainly consists of classrooms, but it also has a restaurant, group and working spaces and a library.

From the vocational school, the room 2027 was selected for the analysis. The room operates as a computer classroom. All required documents were available in the control strategy of ventilation system.

#### Ventilation system

The AHU that ventilates room 2027 serves other classrooms as well. Figure 58 shows the ventilation design for room 2027. The room has two supply air diffusers, one exhaust air device and two dampers. All the supply airflow is controlled by damper 2027IMS.5 and all of the exhaust airflow is controlled by damper 2027IMS.10. Together the dampers are named damper pair 2027.

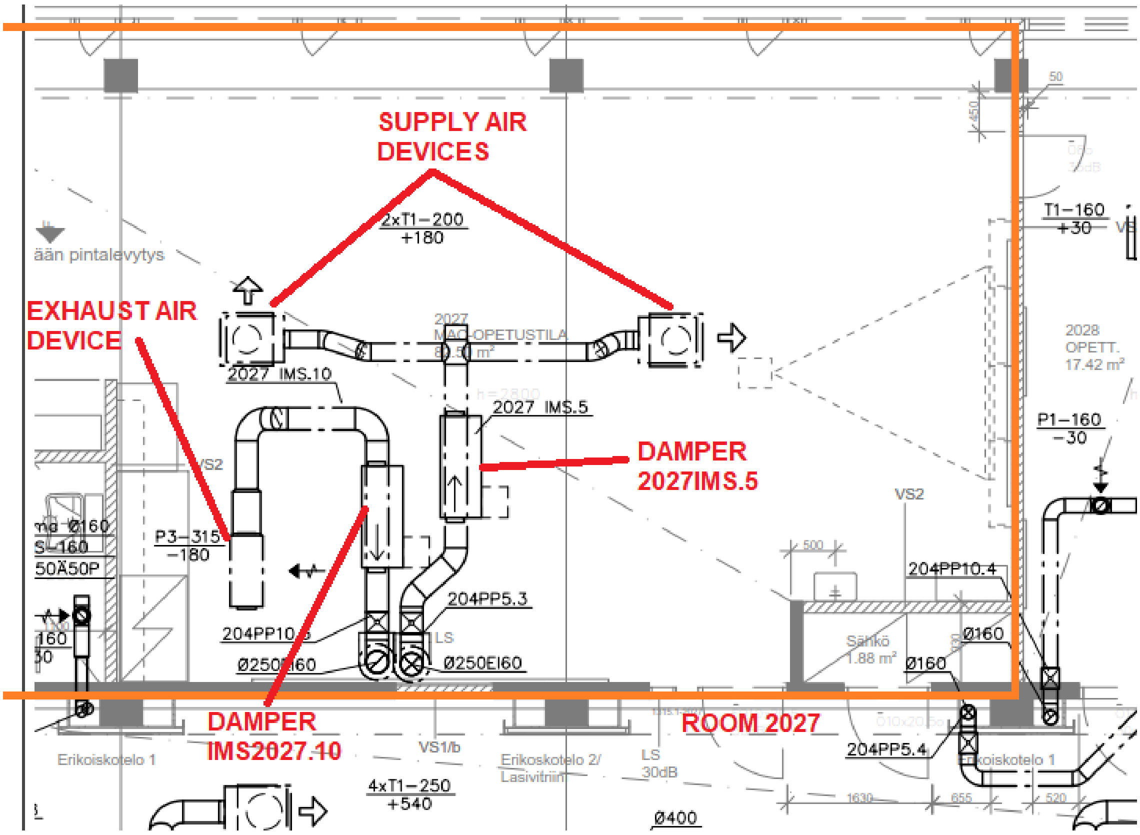

Figure 58. Ventilation design of room 2027 in the vocation school.

### Ventilation automation

Room 2027 airflows depends on occupancy, temperature and $CO_2$ concentration. The ventilation is in normal mode (30 %) within the set time program and when the room occupancy sensor is triggered. The temperature sensor and the $CO_2$ sensor can set boost mode (90 %). It remains unknown why the designer has set the boost mode on 90 % and not 100 %.

Room specific $CO_2$ sensor controls damper pair 2027 depending on $CO_2$ concentration. When $CO_2$ concentration reaches 700 ppm the dampers start to open relatively to $CO_2$ concentration. This is shown in Figure 59. Maximum boost mode is activated when $CO_2$ concentration reaches 900 ppm.

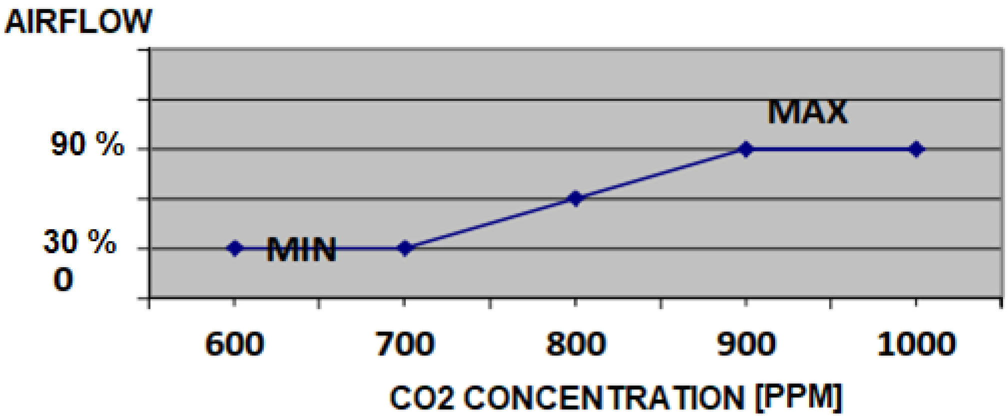


**Figure 59. $CO_2$ sensor controlling damper positions for room 2027.**

Also, the temperature sensor controls damper pair 2027 depending on room air temperature. Damper pair 2027 keeps temperature under the set value of 21 ºC increasing ventilation relatively when room air temperature exceeds the set value. This is shown in Figure 60. Maximum boost mode is activated when the room air temperature exceeds 23 ºC.

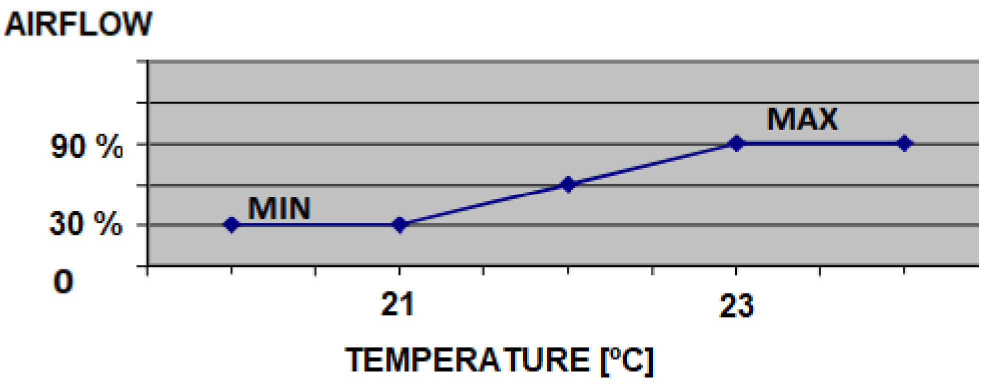


**Figure 60. Temperature sensor controlling damper positions for room 2027.**

If the temperature keeps rising despite airflows being at maximum setting, the fan coils activate. Valves for the fan coils are opened and they start to cool the room. On the other hand, if the airflows are at minimum and the temperature is decreasing then the valves for water radiators open to start heating the room. The ventilation design drawings are lacking information about the control strategy of the supply air temperature.

The supply air temperature depends on the outside air temperature which is presented in Figure 61. When the outside air temperature is -28 ºC or less, the supply air temperature is 19 ºC and when the outside air temperature is 5 ºC or more the supply air temperature is 17 ºC. The supply air temperature changes linearly between 17-19 ºC when the outside air is between -28-5 ºC.

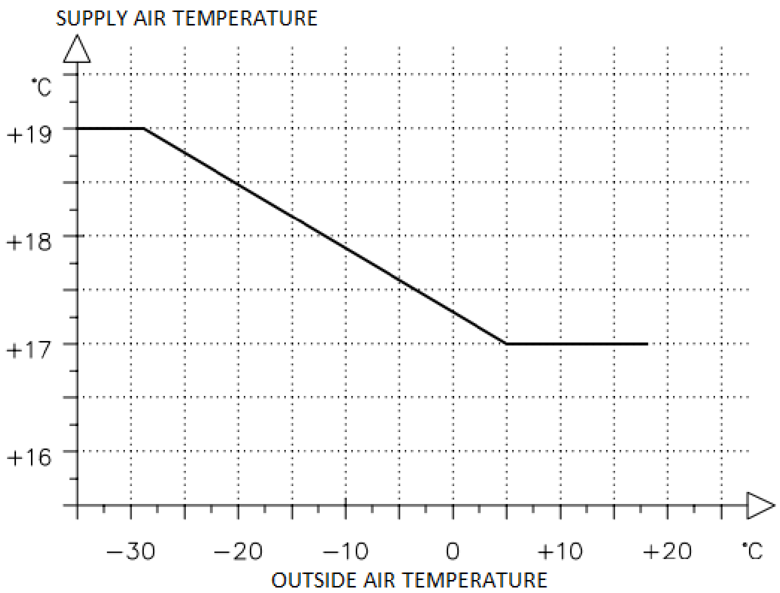


**Figure 61. Supply air temperature depends on the outside temperature.**

### Measured airflows rates

Room 2027 has two identical supply air devices and one exhaust air device. The measurements were done in the normal and boost modes. The results are shown in Table 26.

**Table 26. Measurement results for the vocational school room 2027.**

| | Supply airflow | | | Exhaust airflow | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mode** | **Measured [l/s, l/s m2]** | | Design [l/s] | **Measured [l/s, l/s m2]** | | Design [l/s] | **Difference [l/s]** | **Ratio [%]** |
| **Normal** | **102** | **1.2** | 54 | **117** | **1.4** | 54 | **-15** | **87** |
| **Boosted** | **174** | **2.1** | 180 | **200** | **2.4** | 180 | **-26** | **87** |

In the normal mode, the airflows are almost doubled to the designed values and in the boost mode the airflows are close to the designed values. The designed supply airflow is only 2.25 l/s/m$^2$ which is below the minimum value from Sisäilmayhdistys ry's standard of 3 l/s/m$^2$. The ratios between supply and exhaust airflows in the both modes are causing slight under pressure over the envelope and surrounding area.

### Monitoring measurements

Monitoring measurements were done for temperature levels with TinyTag for room 2027. The room did not have suitable place for pressure difference monitoring of supply air devices. Automation data was available for the temperature sensor and for the supply air damper position.

Figure 62 shows the correlation with damper position and room air temperature. The damper position and the room air temperature measured by the temperature sensor correlate very strongly with each other. Every time the temperature sensor measures temperature over 21 ºC, the supply air damper starts to open. The exhaust air damper is always in same position as the supply air damper.

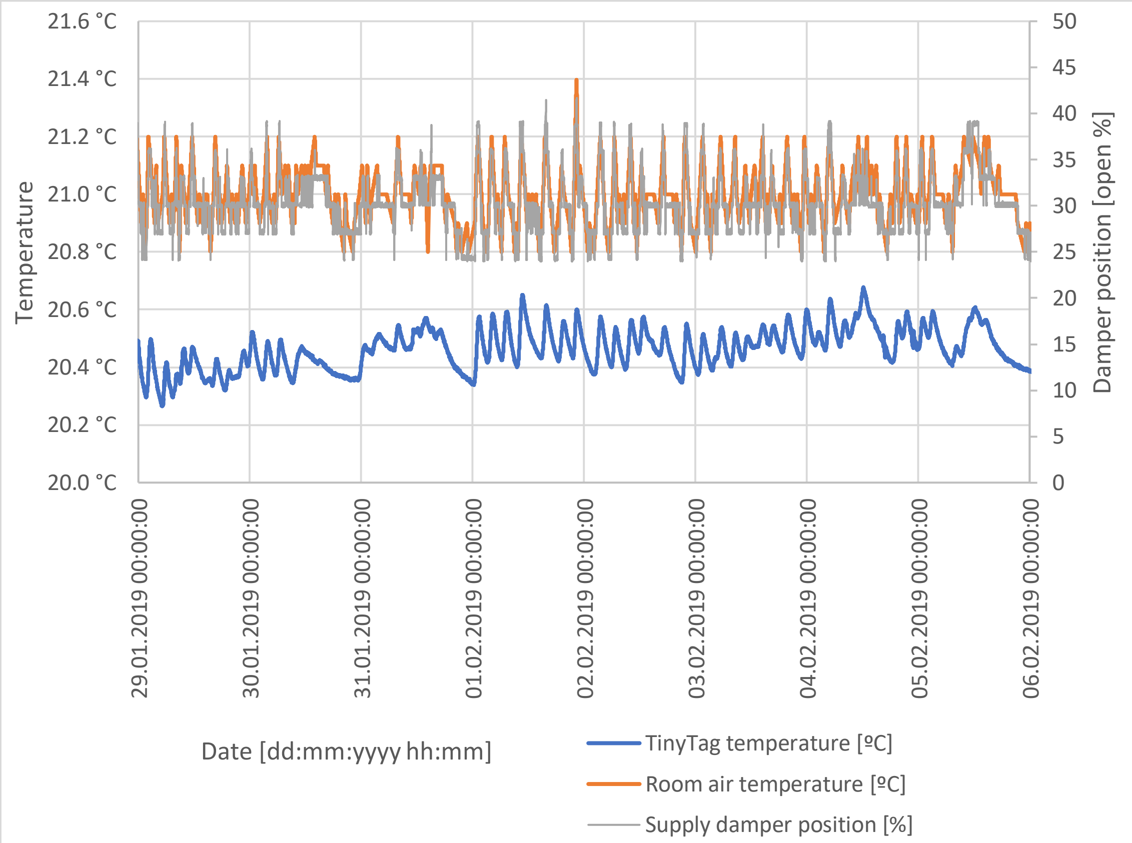


**Figure 62. Temperature monitoring measurement compared to the temperature sensor's measurements and supply air damper position.**

The room air temperature stays within the designed boundaries. TinyTag measurements show that the room air temperature is very stable between 20.2-20.8 ºC never exceeding the room set temperature of 21 ºC.

Automation data was not available for the $CO_2$ sensor and therefore it cannot be known how damper pair 2027 reacts to $CO_2$ concentration. Also, there was no automation data on the occupancy sensor.

## Conclusion

The airflows in the normal mode are doubled compared to the designed values. In the boost mode, the airflows are similar to the designed values fulfilling the supply airflow requirements for Sisäilmayhdistys ry's standards for class S3 of 6 l/s/person if the room is designed for 30 people but not 3 l/s/m$^2$. When designing the standard (3 l/s/m$^2$ or 6 l/s/person) which results in higher airflows should be chosen. In both modes, the ratio between supply and exhaust airflows are not causing too much under pressure over the envelope and surrounding area.

The results from monitoring measurements indicate that the boost mode correlates properly with temperature. The room air temperature stays between 20.2-20.8 ºC, measured by TinyTag, which shows that the room air temperature is very stable. Damper pair 2027 opens only 25-40 % during the whole measurement period showing that the airflows are also stable and not changing between normal and full boost modes constantly.

It remains unknown how the dampers react to $CO_2$ concentration since there is not any automation data available on the $CO_2$ sensor. Additionally, the ventilation drawings had no information about the control strategy of AHUs including the control of the supply air temperature.

## 5.9 Summary

This chapter summarizes the main results of the eight buildings and their respective rooms used for the sample to get a better overall view and cross evaluation of the properties. Only one of the eight rooms analyzed in this study can be determined to function properly. Learning Centre had similar airflows to the designed values and also the room air temperature stayed within the designed boundaries. All the other rooms had problems with airflows not matching the designed values.

### Airflows

The airflow measurements were done for exhaust and supply airflows for each room in normal and boost modes. Table 27 shows the results of the measurements compared to the designed values including the ratios of measured supply and exhaust airflows.

**Table 27. Airflows measurement results from analyzed rooms.**

| Building | Mode | Supply airflow [l/s] | | | Exhaust airflow [l/s] | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Measured | Design | Functionality | Measured | Design | Functionality | Ratio [%] | Functionality |
| Dipoli | Normal | 118 | 50 | **No** | 33 | 50 | **No** | 361 | **No** |
| | Boost | 81 | 100 | **No** | 24 | 100 | **No** | 336 | **No** |
| Väre | Unocc. | N/A | N/A | **N/A** | N/A | N/A | **N/A** | N/A | **N/A** |
| | Normal | 22 | 17 | **No** | 16 | 17 | **Yes** | 138 | **No** |
| | Boost | 30 | 25 | **No** | 25 | 25 | **Yes** | 120 | **No** |
| OK1 | Normal | 58 | 50 | **Yes** | 76 | 50 | **No** | 75 | **No** |
| | Boost | 105 | 100 | **Yes** | 133 | 100 | **No** | 78 | **No** |
| OIH | Normal | 38 | N/A | **N/A** | 49 | N/A | **N/A** | 78 | **No** |
| | Boost | 44 | 80 | **No** | 53 | 80 | **No** | 83 | **No** |
| Learning Centre | Normal | 20 | 20 | **Yes** | 22 | 20 | **Yes** | 88 | **Yes** |
| | Boost | 38 | 40 | **Yes** | 45 | 40 | **Yes** | 85 | **Yes** |
| TUAS | Normal | N/A | N/A | **N/A** | N/A | N/A | **N/A** | 68 | **N/A** |
| | Boost | 78 | 100 | **No** | 106 | 100 | **Yes** | 73 | **No** |
| School in Helsinki | Normal | 56 | N/A | **N/A** | 36 | N/A | **N/A** | 157 | **No** |
| | Boost | 143 | 180 | **No** | 81 | 180 | **No** | 176 | **No** |
| Vocation school | Normal | 102 | 54 | **No** | 117 | 54 | **No** | 87 | **No** |
| | Boost | 174 | 180 | **Yes** | 200 | 180 | **Yes** | 87 | **Yes** |

Table 27 shows that only in Learning Centre the airflows are similar to the designed values. The ratios between the supply and exhaust airflows are within acceptable boundaries in Learning Centre meaning which has the only properly functioning ventilation system in this study concerning airflows. In other buildings the measured airflows do not match the designed values or the supply and exhaust airflows are not in balance.

### Monitoring measurements

Weeklong temperature monitoring measurements were done for each room. Only for Open Innovation House (OIH) pressure monitoring measurements were done because the measurement devices could not properly be attached to other supply air devices.

The temperature monitoring measurements show that the room temperature levels stay inside the designed boundaries in all rooms. For some rooms the designed temperature levels could not be determined but it can be stated that in these rooms the temperature stayed within acceptable levels.

One mean to determine the functionality is to compare the monitoring measurement data against automation data or just by analyzing automation data by itself. For example, by simply looking at the room specific automation data, it can be noticed if the boost mode is constantly on, which indicates that the ventilation system is not functioning properly. Trying to find out the same information with manual measurements is considerably more arduous. Table 28 shows the availability of automation data for room specific sensors and dampers.

**Table 28. Available automation data for room specific sensors and dampers.**

| Automation data availability | Room specific sensors | | | |
|---|---|---|---|---|
| | **Occupancy** | **Temperature** | **$CO_2$** | **Damper control** |
| **Dipoli** | N/A | No | No | No |
| **Väre** | No | Yes | N/A | No |
| **OK1** | No | Yes | Yes | No |
| **OIH** | N/A | No | No | No |
| **Learning Centre** | No | No | No | No |
| **TUAS** | No | No | No | No |
| **School in Helsinki** | N/A | No | No | No |
| **Vocational School** | No | Yes | No | Yes |

Unfortunately, in the most of the buildings the ventilation systems do not record any room specific automation data even though they could. All room specific automation data is not being recorded in any building.

### Room conditions

Despite a dysfunctional ventilation system, the rooms can still have good room conditions. Table 29 shows room conditions for each room while taking into account temperature $CO_2$ concentrations and airflows. The temperature is defined as good if it stays within the designed boundaries, and same goes with $CO_2$ concentration. OK1 had the only room that had automation data available for $CO_2$ concentration and therefore $CO_2$ conditions cannot be defined for the other rooms. The airflows are defined as good if they are the same as the designed airflows or higher.

**Table 29. Room conditions.**

| Building | Temperature | $CO_2$ | Supply airflows | |
|---|---|---|---|---|
| | | | **Normal mode** | **Boost mode** |
| Dipoli | GOOD | N/A | GOOD | TOO LOW |
| Väre | GOOD | N/A | GOOD | GOOD |
| OK1 | GOOD | GOOD | GOOD | GOOD |
| OIH | GOOD | N/A | N/A | TOO LOW |
| Learning Centre | GOOD | N/A | GOOD | GOOD |
| TUAS | GOOD | N/A | N/A | TOO LOW |
| School in Helsinki | GOOD | N/A | N/A | TOO LOW |
| Vocational school | GOOD | N/A | GOOD | GOOD |

The supply airflows for teaching spaces are either 6 l/s/person or 3 $l/s/m^2$ in minimum from which the on the results in greater airflow is chosen. In the school in Helsinki the measured supply airflows did not reach these minimum values being only 2.3 $l/s/m^2$. In the vocational school the measured airflows were similar to the designed values, but the designed supply airflows were only 2.25 $l/s/m^2$. In both schools the airflows are too low to fulfill the minimum requirements for supply airflow.

# 6 Discussion

New regulations in Finland and EU directives force buildings, especially new ones, to become more energy efficient. DCV systems are able to save energy while maintaining proper IAQ by reducing unnecessary ventilation. However, based on literature, case studies, and professionals' experiences, designing, installing, and operating DCV systems can be challenging due to their complexity.

The detected faults of this study were found in many different layers in the ventilation systems. There were problems with designs, balancing, sensors, and installation. Even though the airflows did not match the designed values it was still possible that the room conditions were good.

The room conditions were defined by comparing if the supply airflows matched or exceeded the designed airflows and if the temperature stayed within the designed limits. It is worthwhile to mention that it was not studied if the designed supply and exhaust airflow values actually resulted in good room conditions. Even though the ventilation did not work according to the design in most of the buildings, the temperature stayed within the designed boundaries in all buildings. Also, in some buildings the supply airflows contributed in good room conditions even when they did not match the designed values by exceeding them. It can be concluded that the functionality of the ventilation system cannot be defined by only measuring room conditions, and additionally, a ventilation system that does not function properly does not always lead to bad room conditions.

There were many practical challenges with the field measurements which could be avoided by being more careful in the designing, installing or acquiring phase. For example, in Väre measuring the supply airflow was challenging. The supply air diffuser had no pressure tubes. Also, an airflow horn could not be used to measure the supply airflow because the supply air device was connected to a Halton AVA radiant panel and part of the supply air flowed through the diffuser and part on top of the radiant panel. This is why the airflows in Väre were converted from damper positions. In Dipoli the supply air diffuser was designed for higher airflows. The airflows measurements with pressure tubes are not reliable when the airflows are too low compared to the diffuser's designed airflows. Small differences in the measured pressure differences from pressure tubes result in major differences in the converted airflows. Consequently, an airflow horn was used to measure supply airflows in Dipoli.

In most of the diffusers the pressure tubes were shoved inside the diffuser which made them difficult to reach. The pressure tubes could be dug out with a help of metal wire bent to a shape of a hook. For example in Learning Centre and OK1, the pressure tubes were nicely folded to the grille for easy access to make the measurement process more convenient. In TUAS, the pressure tubes were actually stuck between the joint of the diffuser. It can require a fair amount of force to free the tubes which can result in the tube also breaking away from the diffuser. Reconnecting the tube with the diffuser can be very challenging. Also in TUAS, the damper position of the chilled beam was extremely difficult to determine. The damper controller was in such a difficult angle that the damper position was almost impossible to determine. The airflow measuring process is much more convenient when the pressure tubes, diffuser type plates, diffuser settings and the damper controllers are easily accessible.

Because the problems were on many different levels, it is challenging to prevent and detect them. Automation data is an underrated tool for detecting problems.

In every building room specific automation data was only partly available or not available at all. Only with automation data some of the faults can be detected immediately. For example, it can show if a room is constantly on boost mode if the temperature levels or $CO_2$ concentrations are not staying within the set values. A system that shows only current circumstances is not as helpful. Automation data also supports other diagnostics when analyzed with other measurements. It remains unclear why the ventilation systems are not set to record room specific automation data.

One way to keep ventilation systems functional is to have an inspection for the ventilation systems after a year or two of usage. An inspection includes airflow measurements for each supply and exhaust inlets and outlets. Normally, a ventilation inspection is performed when the building is finished before being occupied. After commissioning and the inspection, the occupants might make changes to the ventilation systems to fulfill their demands. The ventilation systems can be very delicate for changes and might need professional oversight which is not always available. After a year, most of the changes have usually been made and it is advisable to do another checkup for the ventilation systems to determine functionality. The inspection should be done preferably at the ending of the guarantee period.

It is challenging to detect and prevent problems in DCV systems because the problems can occur on many different layers, and on many different phases of design, installation and commissioning. This study concludes that most of the DCV systems do not work properly and it requires another study to learn about the malfunctions and how to repair and prevent them.

Eight buildings were studied from which seven had malfunctioning DCV systems which suggests that approximately 88 % of commercial buildings have malfunctioning DCV systems. The results are prominent. Due to the sampling size, larger scale studies should be performed to learn the true magnitude of the problems with DCV systems.

# 7 Conclusions

The main objective of this study was to define the functionality of DCV systems in eight different buildings with field measurements. The ventilation systems did not have any previous reported faults or errors when the measurements were done. The measurements were done in Finland during winter which means that the buildings were being heated.

The ventilation systems were studied with airflow measurements and a weeklong monitoring measurements. The measurements were analyzed with the ventilation system's automation data and ventilation design drawings.

The results from the field measurements show that most of the ventilation systems do not work properly. Only exception was Learning Centre where the ventilation system did not have any faults. Most of the problems occurred with the airflows that did not match the designed airflow values. When the airflows are not matching the designed values, it can easily lead to an unbalance between the supply and exhaust airflows. In most of the buildings the supply and exhaust airflows were not in balance, which can cause pressure differences to surrounding rooms or over the envelope. The balance of supply and exhaust airflows is important especially in newer buildings since they tend to be more airtight which augments pressure differences.

The faults in DCV systems can be a result of poor system design, maintenance, application, operation or a malfunctioning of a controller, sensor, subsystem or other component. The faults can be difficult to detect due to the whole ventilation system's complexity. None of the problems that occurred were similar. In TUAS the boost mode was constantly on. This was not a result of the temperature levels or the $CO_2$ concentration.

In Dipoli, there was most likely an installation error with the dampers. A likely cause is reversed polarity either in control or supply voltage of the dampers. This is why in normal mode the dampers are open and when boost mode is turned on, the dampers are closed. In both modes the ratio between supply and exhaust airflows was around 3.5 which is enormous. The pressure difference to the room's surrounding were not high which means that the excess air leaks outside the room. Air leakages through structures can transport impurities separating from building materials.

In Väre, the AHU's exhaust duct static pressure is not always staying close to the set value and exceeding it by 450 Pa. This can be caused by a malfunctioning sensor.

In the two classroom that were studied, the supply airflows were not matching the minimum requirements of class S3, 6 l/s/person or 3 l/s/m$^2$, from whichever value gives higher airflows is used. Usually in classrooms the airflows are designed above the minimum requirements to class S2, 8 l/s/person or 4 l/s/m$^2$. In the school in Helsinki the measured airflows did not reach the designed values to fulfil the minimum airflow requirements of class S3. In the vocational school the measured airflow values matched the designed values but the designed airflows were too low to fulfil the requirements even for class S3. When the classrooms are being used at full capacity the airflows are not enough to maintain a proper IAQ. There has most likely been a major error when designing, acquiring or installing the ventilation systems since classrooms should have class S2 airflows.

Despite the malfunctioning ventilation systems, in most of the buildings room conditions were good. According to temperature monitoring measurements and airflows measurements, in most of the buildings the room temperatures stayed in the designed levels and the amount of supply airflows were sufficient. This shows that the functionality of ventilation systems cannot be defined by only measuring room conditions or occupant satisfaction.

Second objective of this study is to improve the measurement strategy. The measurement methods used were able to analyze the functionality of a ventilation system efficiently but with slight changes the measurements could be even more beneficial. Firstly, before doing any measurements, it is worthwhile to ensure that the ventilation system records all necessary data that can be useful for the study. Automation data can be very useful to detect faults. Secondly, monitoring measurements for $CO_2$ concentrations would bring more insight about room conditions and how the ventilation system reacts to it. Thirdly, before travelling into any location for measurements, it is important to fully understand how the ventilation system works, and especially to figure out the models of the air diffusers to have the right equipment for measurements. This way the diffusers' k-factors is also known to transfer the measurements into airflows on the spot for quick analysis. If possible, it is advisable to visit the location beforehand to study the ventilation system.

## References

*Halton - Vario Design Guide.* (2019) Available at: https://www.proidea.hu/halton-kft-228755/halton-vario-szellozteto-rendszer-358629/a_23_d_9_1489069249498__halton_vario_szelloztetorendszer_tervseg_en.pdf.

*Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta* (2017), Helsinki, Finland: The Ministry of Environment.

Ahmad, M.W., Mourshed, M., Mundow, D., Sisinni, M. and Rezgui, Y. (2016) 'Building energy metering and environmental monitoring–A state-of-the-art review and directions for future research', *Energy and Buildings,* 120, pp. 85-102.

Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A. and Elsarrag, E. (2016) 'Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature', *International Journal of Sustainable Built Environment,* 5(1), pp. 1-11.

Artola, I., Rademaekers, K., Williams, R. and Yearwood, J. (2016) *Boosting Building Renovation: What Potential and Value for Europe? Study.* European Parliament.

Björkroth, Eskola and Rönkkä (2018) *Sisäilmastoseminaari.* Porvoo: Bookwell Oy.

Chatzidiakou, L., Mumovic, D. and Dockrell, J. (2014) 'The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students', *The Bartlett, UCL Faculty of the Built Environment UCL Institute for Environmental Design and Engineering London*.

D2 Suomen rakentamismääräyskokoelma (2003) *Rakennusten sisäilmasto ja ilmanvaihto Määräykset ja ohjeet 2003*.

Directive, E. (2002) 'Directive 2002/91', *EC of the European Parliament and of the Council of,* 16.

Du, Z. and Jin, X. (2007) *Detection and diagnosis for multiple faults in VAV systems*.

Energiatehokkuus, R. (2012) 'Suomen Rakentamismaarayskokoelma D3', *Maaraykset ja ohjeet.*

European Commission (2017) 'Energy > Topics > Energy > Efficiency > Buildings'.

European Union (2018) *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance)* European Union.

Fahlén, P. (2010) *Demand-controlled ventilation-Limitations and definitions.*

Finlex (2015) *Ilmastolaki.* Available at: https://www.finlex.fi/fi/laki/ajantasa/2015/20150609.

Finnegan, M.J., Pickering, C.A. and Burge, P.S. (1984) 'The sick building syndrome: prevalence studies.' *Br Med J (Clin Res Ed),* 289(6458), pp. 1573-1575.

Fisk, W.J. and De Almeida, A.T. (1998) 'Sensor-based demand-controlled ventilation: a review', *Energy and Buildings,* 29(1), pp. 35-45.

Gasana, J., Dillikar, D., Mendy, A., Forno, E. and Vieira, E.R. (2012) 'Motor vehicle air pollution and asthma in children: a meta-analysis', *Environmental research,* 117, pp. 36-45.

Hänninen, O. and Asikainen, A. (2013) 'Efficient reduction of indoor exposures-Health benefits from optimizing ventilation, filtration and indoor source controls'.

Hilden, S. (2014) 'Julkisten rakennusten sisäilmaongelmat – paljonko on paljon', 24.10.

Kopra, J. (2018) 'Smart Room Systems for Retrofitted Educational Buildings'.

Kosonen, R. (2018) *Lecture material: EEN-E4001 - Comfortable and Healthy Indoor Environments, 03.01.2018-14.02.2018*, Otaniemi, Espoo: Aalto University, School of Engineering, Department of Energy Techonology.

Liang, Y., Meng, Q. and Chang, S. (2017) 'Fault diagnosis and energy consumption analysis for variable air volume air conditioning system: a case study', *Procedia Engineering,* 205, pp. 834-841.

Maripuu, M. (2011) 'Demand controlled ventilation (DCV) for better IAQ and Energy Efficiency', *REVHA Journal,* 48(2), pp. 26-30.

Maripuu, M. (2009) 'Demand Controlled Ventilation (DCV) Systems in Commercial Buildings', *Functional Requirements on Systems and Components. (Chalmers University of Technology, Building Services Engineering), Gothenbur.*

Mattinen, M., Heljo, J. and Savolahti, M. (2016) 'Rakennusten energiankulutuksen perusskenaario Suomessa 2015-2050'.

Merema, B., Breesch, H., Sourbron, M., Verplaetsen, J. and Van den Bossche, P. (2015) *Demand controlled ventilation in practice: Case study.*

Mølhave, L. and Krzyzanowski, M. (2003) 'The right to healthy indoor air: status by 2002', *Indoor air,* 13, pp. 50-53.

Mundt, E., et al (2004) *REHVA Design Guide No. 2. Ventilation Efficiency* REHVA.

Mysen, M., Schild, P. and Cablé, A. (2014) 'Demand-controlled ventilation–requirements and commissioning. Guidebook on well-functioning and energy-optimal DCV'.

Novoselac, A. and Srebric, J. (2003) 'Comparison of air exchange efficiency and contaminant removal effectiveness as IAQ indices'.

Okochi, G.S. and Yao, Y. (2016) 'A review of recent developments and technological advancements of variable-air-volume (VAV) air-conditioning systems', *Renewable and Sustainable Energy Reviews,* 59, pp. 784-817.

Persily, A. and de Jonge, L. (2017) 'Carbon dioxide generation rates for building occupants', *Indoor air,* 27(5), pp. 868-879.

Reijula, K., Ahonen, G., Alenius, H., Holopainen, R., Lappalainen, S., Palomäki, E. and Reiman, M. (2012) 'Rakennusten kosteus- ja homeongelmat'.

Reinikainen, E., Loisa, L. and Tyni, A. (2015) *FInZEB-hanke Loppuraportti.* Granlund Oy. Available at: https://tem.fi/documents/1410877/2735615/FInZEB_loppuraportti.pdf/6527928a-809b-4870-9e3e-425fe26c15d1.

Satish, U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S. and Fisk, W.J. (2012) 'Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance', *Environmental health perspectives,* 120(12), pp. 1671-1677.

Schild, P.G. and Mysen, M. (2011) 'Requirements for well functioning Demand Controlled Ventilation'.

Seppänen, O., Lönnqvist, S., Säteri, J., Railio, J., Strand, T., Ahola, M. and Niemelä, T. (2017) 'Ilmanvaihdon mitoituksen perusteet', *Helsinki.FINVAC ry.*

SFS-EN 15251, S. (2007) 'Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics', *Suomen Standardoimisliitto,* .

SFS-EN ISO 7730, S. (2005) 'Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPV indices and local thermal comfort criteria (ISO 7730:2005)', *Suomen standardoimisliitto*.

Sisäilmayhdistys ry (2018) 'Sisäilmastoluokitus 2018. Sisäympäristön tavoitearvot, suunnitteluohjeet ja tuotevaatimukset'.

Spengler, Samet and McCarthy (2001) *Indoor Air Quality Handbook.* McGraw-Hill.

SULVI (2017) *Uusi asetus rakennuksen sisäilmastosta ja ilmanvaihdosta sekä FINVACin oppaat julkaistu.* Available at: https://sulvi.fi/uusi-sisailma-ja-ilmanvaihto-asetus/ (Accessed: 16.3.2019).

Sundell, J. (2004) 'On the history of indoor air quality and health', *Indoor air,* 14(s 7), pp. 51-58.

Vuoti, E. (2018) 'Sisäilmatutkijan ilmanvaihto-opas'.

Wang, S., Ang, H.M. and Tade, M.O. (2007) 'Volatile organic compounds in indoor environment and photocatalytic oxidation: state of the art', *Environment international,* 33(5), pp. 694-705.

WHO (2000) *The Right to Healthy Indoor Air.* Available at: http://ecojustice.net/2010-ENVRE145/PDF/20100323-Adamkiewicz-Molhave-Right.pdf.

Wyon, D.P. (2004) 'The effects of indoor air quality on performance and productivity', *Indoor air,* 14(7), pp. 92-101.